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Low-Energy Dwelling Prototypes for Different Regions of Chile

Gabriel Felmer

Thesis submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

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Architectural Association School of Architecture
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Low-Energy Dwelling Prototypes for Different Regions of Chile

Abstract

The central problem addressed by this research is the fuel poverty caused by the thermal inefficiency of new dwelling stocks in Chile. By performing simulations to investigate different design options, dwelling types, building materials and passive envelope techniques, this research demonstrates that acceptable indoor thermal comfort conditions can be achieved in dwellings at low extra-capital and without recourse to conventional space-heating and cooling. The planned outcome of the study is a modular low-carbon prefabricated prototyping system that use locally sourced timber materials for delivering naturally conditioned dwellings at different multi-unit configurations and scales and to a number of site locations nationwide.

Keywords: *Fuel Poverty, Housing Strategy, Passive Design, Low-Carbon Prototypes*

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1 Introduction

1.1 Problem Statement

Low-income households in Chile are living in fuel poverty, defined as the inability to have adequate energy services for a reasonable proportion of income. A recent report by the United Nations Economic Commission for Latin America and the Caribbean (ECLAC, 2009) revealed that Chile has among the highest rate of fuel poverty in Latin America —where the poorest quintile of households spends more than 16% of their income on fuels. The current extent of fuel poverty has been explained by researchers due to combination of high fuel prices, low-income, and energy inefficient dwellings (Campos, 2016; Cerda & Gonzales, 2017; García, Arce, & Croxford, 2012). Besides the burden on household capital income, emissions due to fuel combustion for domestic space-heating are responsible for high levels of air-pollution in cities (MMA, 2014), exposure to toxic chemical gases in dwellings (Cortés & Ridley, 2013), and in combination with extremes of high and low indoor temperatures a cause of excess seasonal morbidity and mortality (Grass & Cane, 2008).

Although Chile has a wide array of climates, ranging from hot to cold extremes, most of the population lives in mild temperate regions (INE, 2012). There is great potential for improved housing design to reduce fuel use for space-heating which accounts for one-third of national domestic energy use, 2,190 kWh/year per household, where water-heating accounts for 30%, electric appliances 27%, cooking 12%, and space-cooling 2%, according to latest survey data by MINEN (2010).¹ However, most recent government action has focused on creating programmes to subsidise fuel prices, improve the efficiency of space-heating appliances and ban their use in urban areas where air-pollution is most acute (MINEN, 2013). Similarly, research has focused on improving building thermal insulation, airtightness of building envelopes, and heat recovery to decrease energy use for space-heating (Bustamante, 2001, 2009; Hatt et al., 2012; Figueroa et al., 2013). Efforts to address fuel poverty at its roots have so far been insufficient.

Housing shortage, and the energy and carbon intensity of building construction have placed great pressure on the government to improve the design of new dwelling stock. Present estimates show that in the last decade housing demand has remained four times higher than supply with more than 400,000 dwellings needing to be built per year (CASEN, 2015). The construction of buildings of which 60% is destined to become housing is responsible for one third of national energy use, greenhouse gas emissions (GHG) and so-

Figure 1.1 Standard residential apartment developments

It has been estimated that there are over 5,000 ghettos (or very poor segregated urban communities) in Chile created from poorly designed multi-apartment complexes (ATISBA 2010, 2015). These are massive high density residential developments built with substandard accommodation facilities and low quality constructions located in highly degraded urban areas, characterised by poor public infrastructure and environmental services.



lid waste generation (MINVU, 2013). During this same decade, the intensity of construction increased due to a steep rise in production of apartment dwellings which for the first time exceeded half of new housing stock (INE, 2015). However, thousands of public and private multi-storey apartment developments that turned into slums (ATISBA, 2010, 2015), made this form of accommodation highly unpopular among local authorities, city planners and researchers (Figure 1.1). Whether apartment buildings failed per se to provide adequate living conditions is questionable since compared to houses apartments have a better potential to improve housing environmental performance by means of achieving occupant thermal comfort and reducing additional energy use for space-heating (Damico et al., 2012; Hachem et al., 2014).

Research to improve energy performance of residential buildings has left many unsolved issues that are worth addressing to appreciate the extent of fuel poverty. Studies by Bustamante (2001, 2005), show that in Northern Chile passive design of dwellings helps improve thermal comfort and achieve annual energy demands for space-heating in the 5–10 kWh/m² range —assuming a whole-house 24-hour thermostat of 20°C with night-time set back of 17°C; air-exchange rates of 1.0 ac/h, and internal heat gains of 8.0 W/m². This region located from the north central valley to north-end of the country, comprising over 10% of population was called by Bustamante a ‘zero-energy demand zone’ (2001, p132). Studies by Müller (2003, 2006) performed for detached dwellings in Santiago, Central Chile, provide evidence that this low energy demand zone can be expanded to a much larger section of population. However, while there is urgent need to reduce space-heating energy in central and southern regions where fuel poverty is most severe, the potential of apartment configurations to improve energy performance has not been explored sufficiently.

Improving the design of apartment buildings can offer an opportunity to reduce fuel poverty in housing. The thermally inefficient stock of suburban detached and semi-detached dwellings has raised a wide public debate concerning whether to develop higher density housing in inner-city areas instead (UTPCh, 2013). There is wide body of research arguing that new housing de-

sign should evolve in this direction to reduce demands for urban land, air-pollution and GHG emissions (UN-Habitat 2011, 2012; MINVU, 2013). There is a knowledge gap regarding the advantages of apartments to reduce fuel use and carbon emissions during construction and operation, and a need to better understand their dynamic thermal performance. Although recent research shows that apartment dwellings can help reduce energy demands during the cold season (Damico et al., 2012; Sanaieian et al., 2014) little is known about their response during warm seasons where the duration and intensity of hot spells are due to increase with climate change (ECLAC, 2012; MMA & GEF, 2016).

Further research is needed to improve the thermal performance of residential buildings. Studies by Bustamante (2001, 2005) to improve dwellings specified to state regulations show that for a typical warm season day in Santiago indoor temperatures could be maintained below 30°C without need for conventional cooling. However, over the heating season, temperatures could not be raised above 16°C, an accepted minimum to safeguard thermal conditions in residential buildings (Peeters & de Dear, 2009). While acceptable temperatures were reached for the cooling season in most regions, annual space-heating energy demands in central and southern regions could not be reduced below 80–180 kWh/m². Since much housing stock is due to be built, more than half of its projected size by 2050 (CASEN, 2015), it would be worth developing a method to design dwellings that could be operated without energy other than the passive gains from occupancy and solar gains.

This thesis aims to contribute to the issue of fuel poverty in Chile proposing more efficient dwelling designs that will help reduce energy and eliminate current dependence on fuels. The focus is on achieving acceptable indoor thermal comfort conditions without need for conventional space-heating or cooling. The studies by Bustamante (2006; 2009) and Müller (2006) estimated energy demand using fixed thermostat settings, 20°C and 26°C respectively. The present study is based on a broader comfort band as suggested by recent research in Chile (CNE, 2008) and internationally (de Dear et al., 1997, 2011; Humphreys et al., 2013).

The research undertaken for this thesis has compared the performance of state housing with alternative dwelling designs, investigated contribution of alternative construction materials, and reviewed passive design techniques for different locations across Chile. The design techniques that were applied cumulatively comprised in the same order: ensuring adequate thermal capacity is available in dwellings, increasing statutory thermal insulation, adjusting glazing properties, and providing practicable envelope elements —insulated shutters, window-frame vents, exterior louvers and window openings. The results show that it is possible to do away with conventional space heating and cooling in most of the country.

1.2 Research Aim and Objectives

The primary aim of this study is to improve the thermal performance of new dwelling designs for reducing the burden of fuel costs and combustion emissions. The planned outcome of the research is a construction system of pre-

fabricated timber panels that can suit different dwelling configurations and is easy to transport and assemble in different locations (**Figure 1.2**). The study addresses the thermal comfort needs of households in low-income by designing dwellings whose individual construction costs are no more than 400 USD per square meter of floor area. The target is to provide indoor temperatures that are allowed to drift naturally within acceptable comfort ranges with no recourse to conventional energy. The outcome of the study is assessed for different climates in Chile with extensive parametric simulation analysis performed for its central, north and south regions, specifically for locations in Santiago, Antofagasta and Puerto Montt. Other objectives are to:

- assess the contribution of passive design techniques and use of different operable envelope components
- investigate the thermal performance of different building design options, dwelling types, and construction materials
- design a building prototype that can be built, operated and disassembled with minimal use of conventional energy sources

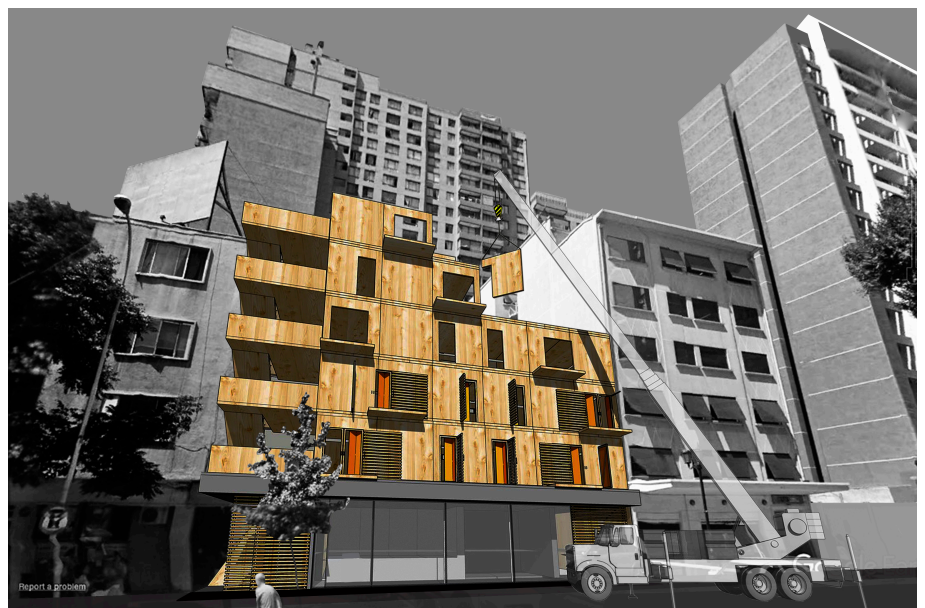
1.3 Significance of the Study

It is expected that the results of the research can be applied to different regions in Chile and to developing countries alike. Further research could focus on reducing demand for other energy uses in housing such as electric appliances, water-heating and cooking or the energy-intensity of construction. Improved thermal performance of housing has numerous other benefits:

- increases household disposable income
- improves indoor thermal comfort, air-quality, and daylighting
- increases scope to achieve energy self-sufficiency with renewables
- reduces dependency on imported fossil-fuels, GHG and non-GHG pollutant emissions

Figure 1.2 Erection of a low-carbon infill apartment development

The project proposed from the outset of this thesis seeks to accommodate families of low and middle income in an abandoned inner-city plot in Santiago. The initiative is part of a series of self-managed housing projects developed by a non-governmental organisation (MPL; *Movimiento de Pobladores en Lucha*) that empowers low-income slum dwellers to occupy public vacant plots in well serviced inner-city areas.



1.4 Structure of the Thesis

The thesis is organized into four sections. Firstly, it discusses the parameters influencing fuel poverty in dwellings by reviewing recent research on thermally efficient design of buildings. Secondly, it sets out a national strategy for building and operating naturally conditioned dwelling prototypes for different regions across Chile. Thirdly presents results of dynamic computational simulations to validate the energy and environmental performance of prototypes. Fourthly, it presents example dwelling designs that illustrate the applicability of the research. A more detailed breakdown of the thesis is given below.

1 Introduction

Problem statement

2 Fuel Poverty in Housing

Definition and assessment of fuel poverty in dwellings, review of design variables influencing fuel consumption and thermal comfort in residential buildings. Discussion of findings from evidence gathered in this study

3 Towards a New Housing Strategy

Formulation of a housing strategy for reducing fuel poverty by analysis of the national dwelling stock. Definition of standard dwelling designs based on typical building characteristics, statutory regulations and standards, and minimum environmental requirements

4 Design of Naturally Conditioned Dwellings

Assessment of passive design strategies to improve the thermal performance of standard dwelling designs. Results of dynamic thermal simulations performed for different dwelling types, building constructions, and envelope element designs. Overview of regional design variations

5 Delivering Low-Carbon Prototypes

Graphical explanation of design principles through the proposal of a construction system to digitally fabricate, build and deliver low carbon dwellings. Summary of design recommendations and construction guidelines

6 Conclusions

Summary of main findings

¹ The data by the Chilean ministry of energy (MINEN, 2010) is based on a survey performed for 3,220 dwellings across different regions of Chile based on household appliance usage patterns reported verbally by the respondents, not on actual measurements of domestic fuel consumption. The figures estimated by MINEN used in this thesis were disaggregated from firewood, otherwise, space-heating accounts for 5,760 kWh/ year per household, more than half of national energy use (Romero, 2011)

2 Fuel Poverty in Housing

2.1 Introduction

The definition of fuel poverty and the variables influencing energy consumption in dwellings are introduced in this chapter. The main objective is to bring into question the criteria used by researchers and designers to predict energy use for achieving indoor thermal comfort. Results of field studies carried out for this study including measurements of fuel consumption, indoor temperature monitoring and a survey on occupant thermal comfort are also examined.

2.2 Definition and Assessment

Fuel poverty is broadly recognised as a problem rooted in the thermal inefficiency of built dwelling stocks. The concept emerged during the 1980s in the UK from the notion of inadequately heated dwellings defined by Lewis (1982) as: 'the inability to afford adequate warmth in the home'. A decade later, in a seminal book on fuel poverty, Boardman (1991) expanded the concept arguing that fuel poverty occurs when a household spends more than 10% of income on all fuels used in homes, not just space-heating. From there on the definition of fuel poverty has been adapted by researchers to address the social, financial and environmental impacts of energy efficiency measures to reduce fuel consumption in dwellings mostly in Europe (Buzar, 2007; Tirado et al., 2014; Simoes et al., 2016) and recently in Chile through revisions of national socioeconomic statistics (Campos, 2016; Cerda & Gonzáles, 2017).

Fuel poverty is defined as a condition in which a household is unable to have acceptable dwelling conditions, energy sources and appliances to meet thermal comfort (Campos, 2016). Monitoring studies from different countries have found that energy efficiency measures to address fuel poverty through improving dwelling thermal performance do not necessarily result in reducing fuel consumption (Healy & Clinch, 2002, Tirado et al., 2012, 2014; Simoes et al. 2016; Cárdenas, 2015).¹ However, increasingly from low to middle income household groups, alleviation of fuel poverty through energy efficiency has been acknowledged to reduce dependency on fossil-fuels as well as related financial and environmental effects (García, Arce & Croxford, 2012; Tirado et al., 2014; Shueftan & Gonzáles, 2016). Throughout this thesis, different ways of alleviating fuel poverty through improving dwelling thermal performance as well as quantifying the effects of dwelling energy efficiency are investigated.

The definition of fuel poverty adopted for this study draws upon the causes and adverse negative effects of the energy inefficiency of built dwell-

ing stocks in Chile (Collados & Armijo, 2009; DITEC-MINVU, 2009). Evidence from field studies and a review of national building regulations and standards undertaken for this study (see Sections 2.4 and 3.5), led to defining fuel poverty as: *the inability of households to access acceptable thermal comfort conditions without financial hardship nor detriment to indoor and outdoor environments*. In this manner, relevance is also given through the analysis contained in this thesis to the negative financial and environmental effects of fuel consumption for residential space-heating dwellings (MINEN, 2014).

Based on various national sources and evidence gathered in this study, there are several factors to the above definition (**Table 2.1**). The consumption of fuels in dwellings is largely a function of the ability of their occupants to maintain their thermal comfort, individually, or through making changes to the building envelope and HVAC systems (see design variables influencing thermal comfort in section 3.4). The existing body of standards in Chile has been unable to address fuel poverty in housing since energy use in dwellings is generally assessed for energy consumption patterns and mechanical space conditioning systems of developed countries such as the UK and Germany (MINVU & BRE, 2015; CNE & GTZ, 2008). The factors listed in Table 2.1 are set to accord with local occupant behaviour and space-conditioning practices regarding thermal comfort in dwellings, grouped into three main components:

The definition of *thermal comfort* in Chilean dwellings requires investigation (see thermal comfort assessment criteria in Section 3.4). There is consensus among local researchers and developers that acceptable thermal comfort conditions refer to international standards (e.g ASHRAE, ISO, EN). Dwellings are generally assumed being heated and cooled mechanically us-

Table 2.1 Criteria for assessing fuel poverty in dwellings

<i>Component</i>	<i>Factor</i>	<i>Assessment</i>	<i>Source</i>
Thermal comfort	room temperatures	variable range as a function of variations in outdoor temperature and occupant acceptability (see adaptive comfort criteria in Section 3.4)	(de Dear, 2010; Humphreys, 2013)
	conditioned rooms	living areas and bedrooms, unless under-occupied (see energy use assessment criteria in Figure 1.2)	(Boardman, 2010)
	number of hours	9-hours a day for those at work or in full-time education; 16-hours for those likely to be at home all day	see also: scope of analysis in Section 3.2 and 3.4
	supported seasons	3 to 6 months for space-heating in the main inhabited region and up to 3 months for space-cooling	
Financial hardship	proportion of income	10% of net-disposable income based on the Chilean ministry of social development definition	(MDS, 2016)
	vulnerable households	families of low and middle income quintiles with children (18-), elderly (60+) or disabled members	(Campos, 2016)
Environmental impact	outdoor emissions	maximum carbon-dioxide (CO ₂) emission guidelines for space-conditioning appliances	(MINVU, 2016)
	pollution concentrations	24-hour mean indoor concentrations for carbon-dioxide (CO ₂) and combustion pollutants (PM _{2.5} , CO, NO ₂ , SO ₂)	(WHO, 2014)
	outdoor fresh-air supply	minimum air exchange rates of 5.0–8.0 l/s per person in occupied rooms at any given time	(MINVU, 2016)
	indoor daylighting	average room daylight factor of 5% or higher	

Note: net-disposable income accounts for all earnings, benefits, pensions and investments before housing costs and after income taxes

ing whole-house 24-hours fixed thermostat settings of 20°C and 26°C (AChEE 2007; MINVU & BRE, 2015). These criteria do not describe the real situation in dwellings where comfort temperatures drift hourly from day-to-day and nearly all form of adaptation applies: changing clothing, posture, activity or opening a window, closing a blind etc. There is a wide body of recent research showing that when occupants are not used to centralised heating and cooling systems a wider range of temperatures is accepted (Auliciems & Szokolay, 2007; de Dear, 2011; Humphreys, 2013).

Financial hardship: the expenditure threshold typically used to measure fuel poverty is 10% of household disposable income (Boardman, 2010). This figure equals the actual median expenditure of the three poorest quintiles of population in Chile, including all fuel uses (Campos, 2016). Thus, in this study a household is said to be in relative financial hardship when it spends more than 10% of its net-disposable income on fuel and is also vulnerable to low-income according to criteria set by the ministries of housing and social development (MINVU, 2016; MDS, 2016).

Environmental impact: reductions of carbon-dioxide emissions (CO₂), are typically considered benefits of alleviating fuel poverty in dwellings (Cerdeira & Gonzales, 2016). However, current household combustion practices also cause toxic outdoor and indoor concentrations of non-GHG pollutants: particulate matter (PM_{2.5}), carbon monoxide (CO), sulfur (SO₂) and nitrogen dioxides (NO₂) (Cortes & Ridley, 2013; MMA, 2014). The chemicals emitted from the combustion of fuels are major cause of high prevalence of premature deaths, respiratory diseases, burns and poisoning (WHO, 2014). Design measures for improving thermal comfort in dwellings should do so without detriment to the environment of the home paying particular emphasis to the provision of adequate daylight, outside fresh-air and indoor air-quality levels.

Fuel poverty is typically recognised as a problem caused by three main factors: high fuel prices, low-income and energy inefficient dwellings (Armijo et al., 2009; Hatt, 2012; Campos, 2016). Most of present government policies in Chile focus on addressing the immediate problems with fuel consumption, for instance, offering financial incentives to lower fuel prices and allowances to off-set high space-heating costs (MINEN, 2015; MIDEPLAN 2015). Although addressing fuel prices and low-income contribute to mitigate the burden of fuel costs on households, these factors are largely subjected to the volatility of the national economy. A more comprehensive and long-lasting approach to address current dependence on fuels would be minimising energy demands by investing on more thermally efficient dwelling designs.

2.3 Dwelling Performance Parameters

The parameters influencing thermal comfort in buildings, namely the metabolic rate and clothing of occupants and environmental variables (air and radiant temperatures, relative humidity and air-speed), are influenced by two modes of operation (Humphreys, Nicol, & Roaf, 2016). Dwellings in Chile are most of the time operated *free-running*, meaning that the energy gains from occupancy and solar radiation are sufficient to maintain minimum acceptable indoor comfort temperatures. However, during brief seasons, dwellings are

operated under a *supported mode* meaning that additional space heating and cooling energy is provided when required by the occupants. The existing body of research has not gone far enough in differentiating between these two modes of operation and their real-life implications on households (Méndez, 2008; García & Croxford, 2012). There is a gap between the criteria used in literature to assess dwelling energy performance and actual fuel consumption causing fuel poverty.

2.3.1 Predicted Energy Consumption

The criteria generally used by designers and researchers to predict fuel consumption in dwellings tend to underestimate the conditions under which occupants are considered comfortable (Bustamante 2001, 2009; AChEE, 2007; Hempel et al., 2013; Encinas & de Herde, 2013). The design temperatures, number of conditioned rooms, hours of occupation, and the season during which conventional space heating and cooling appliances are used are often misjudged, and thus overly high fuel consumption rates are deemed acceptable. As shown in **Table 2.2**, the conventional approach to estimate dwelling energy performance differs with the criteria used in this study to accord with local occupant thermal comfort and fuel consumption patterns, specifically in the following aspects:

Table 2.2 Evidence-based and conventional predicted energy consumption

	<i>Evidence-based criteria</i>	<i>Conventional criteria</i>
Design temperatures	variable range as a function of outdoor temperature and occupant acceptability	fixed thermostat settings of 20°C (heating season) and 26°C (cooling season)
Conditioned rooms	living areas and bedrooms, unless under-occupied	whole-house heating and cooling energy operation
Number of hours	9 or 16 hours a day, when occupants are at home and awake	24-hours energy operation, allowing 8-hours set-back settings
Supported seasons	3 to 6 months heating season; 3 months cooling season	6 months heating season; 6 months cooling season

Note: indicative criteria used for estimating space-heating and cooling energy in dwellings (from Bustamante 2009, p.106; Hatt et al., 2012,p.123)

By applying both criteria to predict energy consumption in dwellings, significant discrepancies can be found. Regional variations in space-heating energy in **Figure 2.1**, show that when compared to projections based on actual occupant thermal comfort and appliance operation preferences (**2.1a**), conventional energy predictions can be as much as 200% to 300% overestimated (**2.1b**), assuming dwelling characteristics and all other input parameters being equal (see detailed input assumptions in Appendix 8.5). Over 70% of the difference in predicted energy use is due to misconceptions related to the usage of appliances, such as the number of hours of operation and the area of the house assumed to be heated —changes in design temperatures result in variations in the order of $\pm 15\%$ for each 1°C (Figure 2.1). Differences in predicted energy use are explained because unlike conventional assumptions occupants are actively engaged in the usage of appliances and tend to exercise a variety of additional actions to limit excess energy costs such as

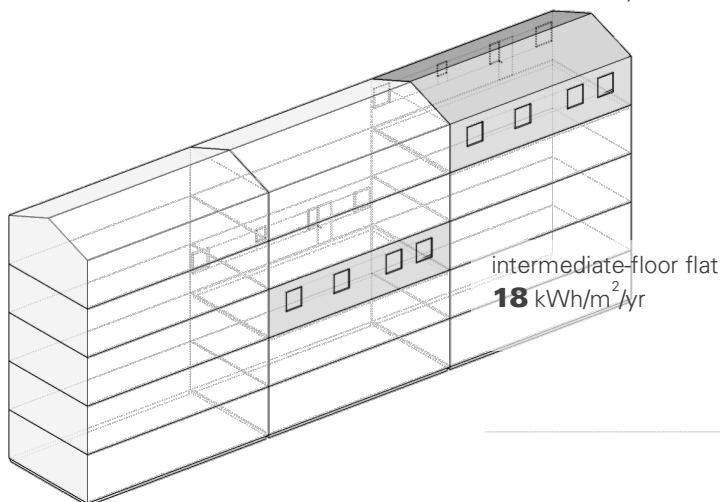
Figure 2.1 Regional variations in space-heating energy for standard base-case dwellings

Space-heating energy is estimated for a base-case or reference case for the purpose of comparison assumed as a 70 m² single-storey detached dwelling built on typical timber-frame constructions complying with minimum statutory requirements by location for roof and wall insulation, single-glazing (5.8 W/Km²) 10% window-to-floor area and 1.0 ac/h infiltration (for each additional 1.0 ac/h increase, space-heating energy will increase by 25% in Antofagasta, by 60% in Santiago and over 80% from Puerto Montt to the south (see results of simulations in Appendix 8.5)

2.1a Energy is estimated for the living area and bedrooms for a 16-hours thermostat setting of 17°C from May to September. **2.1b** (grey figures) Energy is estimated for a whole-house 24-hours thermostat of 20°C with night-time setback of 17°C from April to September (see inputs for simulations in Appendix 8.5).

2.1c Space-heating energy for standard base-case apartments

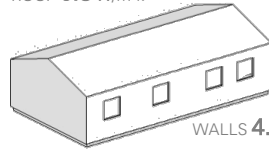
The same plan and specifications for the base case are applied to different apartment units in multi-storey buildings (based on results of simulations for *Santiago*)



Antofagasta = 12 kWh/m²/yr

= 30 kWh/m²/yr

ROOF 0.8 W/m²k



WALLS 4.0 W/m²k

AIR EXCHANGE 1.0 ac/h

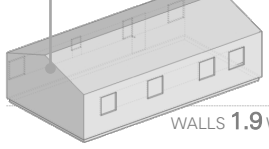
HLC: 7.7 (W/Km²)

Santiago = 25 kWh/m²/yr

= 90 kWh/m²/yr

BC

ROOF 0.4 W/m²k



WALLS 1.9 W/m²k

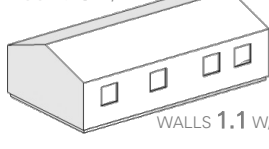
AIR EXCHANGE 1.0 ac/h

HLC: 5.1 (W/Km²)

Pto. Montt = 50 kWh/m²/yr

= 130 kWh/m²/yr

ROOF 0.3 W/m²k



WALLS 1.1 W/m²k

AIR EXCHANGE 1.0 ac/h

HLC: 3.9 (W/Km²)

upper-floor flat
25 kWh/m²/yr

intermediate-floor flat
18 kWh/m²/yr

Calama

= 15 kWh/m²/yr

= 70 kWh/m²/yr

Copiapó

= 10 kWh/m²/yr

= 60 kWh/m²/yr

Valparaíso

= 20 kWh/m²/yr

= 60 kWh/m²/yr

Temuco

= 40 kWh/m²/yr

= 110 kWh/m²/yr

Pta Arenas

= 100 kWh/m²/yr

= 250 kWh/m²/yr

Northern Chile

Central Chile

Southern Chile

Austral Chile

20°

30°

40°

50°

controlling the heat output of space heaters, closing curtains and windows, changing clothing and/or activities, moving to another room, etc.

There are two relevant implications from predicting energy consumption based on field measurements and actual observations in real dwellings (see findings of field studies in Section 2.4). First, it proves that an evidence-based approach to thermal comfort is critical for effectively contributing in alleviating fuel poverty in households. Second, since less energy is actually being consumed in households improved building design to achieve occupant thermal comfort can lead to more affordable alternatives for reducing fuel consumption. It can be inferred from these implications that improving the design of dwellings through changing their inherent physical and operational properties can be a highly efficient way to address current fuel poverty.

2.3.2 Passive Design of Dwellings

Previous research has identified a number of factors influencing the thermal performance of dwellings in Chile. The design of dwellings is mainly a function of the outdoor temperature range and diurnal fluctuation as well as availability of solar radiation and air velocity. The performance of dwellings varies from region to region according to dwelling type, fixed and operable envelope properties (see summary of design variations in Section 4.5). As explained in **Table 2.3**, previous recommendations for passive design of dwellings have placed much emphasis on improving fixed envelope characteristics such as thermal insulation and glazing properties. Yet it is still not clear the difference in performance between dwelling types nor the contributing effect of using operable envelope elements on occupant thermal comfort conditions.

The thermal performance of dwellings is a function of the degree of exposure to the outdoor temperature. Although dwellings in apartment buildings can reach the lowest level of exposure and space-heating energy (**2.1c**), current knowledge is limited to performance of one or two-storey detached and semi-detached houses. These housing types have been traditionally and still are at present the most common and preferred form of accommodation nationally (MINVU, 2015). However, now that most of new dwellings are flats in multi-storey residential buildings (INE, 2015), understanding their full range of performance is compelling. There is a knowledge gap in the existing body of research as to whether thermal comfort can be achieved in apartment flats and whether apartment units can be arranged economically offering the same quality and amenities preferred in traditional houses.

The thermal capacity of the building structure is an influential parameter to contribute in achieving occupant thermal comfort during warm and cool seasons. The thermal capacity of dwellings is determined by the density, specific heat and volume of a layer of building materials. Previous research (Bustamante, 2001; Müller 2003, 2006), has demonstrated that the use of high-density building materials is key to moderate indoor diurnal temperature swings, including studies for concrete, brick and rammed earth constructions (Table 2.3). However, present high capital costs and low seismic response of mainstream heavyweight materials are currently limitations for broader application to multi storey residential buildings.

Statutory requirements for thermal insulation of the building envelope are insufficient to reduce fuel consumption in dwellings (CNE & GTZ, 2008a). Design recommendations have been made by Chilean standard NCh-1079 (INN, 2008) to increase statutory insulation for glazing, exposed walls and roof elements (Table 2.3). However, the problem with these recommendations is that they are made based on 24-hour thermostat settings of 20°C for detached houses. Since this usage pattern would be impracticable with current appliances which are operated intermittently and have no thermostat settings the insulation and glazing requirements given in standard NCh-1079 end up being unnecessarily expensive and contributing to exacerbate overheating in less exposed dwelling types.

Additional passive heating and cooling can be provided in dwellings by adjusting the size and type of glazing and window openings. For the cold season, windows should be designed to provide maximum solar heat gains with minimum night-time heat losses by control of glazing size and insulation properties (Table 2.3). For the warm season, most of unwanted solar gains can be avoided by appropriate orientation of windows and use of exterior adjustable louvers (Hatt et al., 2012). Regular night-time ventilation through window openings combined with high thermal storage capacity can be highly effective for natural cooling of houses (Bustamante, 2001; Müller, 2006). The foreseeable advantages of passively heating and cooling apartment dwellings which have noticeably less exposed envelope areas than traditional detached and semi-detached houses have not been sufficiently appreciated.

Table 2.3 Regional parametric variations for improving dwelling design

	<i>Recommendations from previous studies</i>	<i>Source</i>
Dwelling type	significant improvements in thermal and energy performance can be achieved in least exposed dwelling types	Alvarado (2014); Damico et al., (2012)
Thermal capacity	thermally heavyweight structural materials (traditional concrete, ceramic brick and rammed earth) are recommended to reduce indoor temperature peaks in central valley locations	Bustamante (2001); Müller (2006)
Thermal insulation	above current statutory regulations (CLT, 2007), with U-values increasing from south to north between 0.2–0.8 W/m ² K for exposed roof and 0.3–2.0 W/m ² K for exposed wall elements	Chilean standard NCh-1079 (INN, 2008)
Glazing size	whole-house window-to-floor (WTF) areas increasing from south to north in the order of 15–30% respectively	Bustamante (2001)
Window type	single-glazed windows in northern coastal and interior locations (U=5.8 W/m ² K), and double glazed windows in central and southern regions (U= 2.9 W/m ² K)	Bustamante (2001) Hatt et al.,(2012)
Glazing orientation	preferably north-oriented windows comprising over 70% of the total net-glazing area of dwellings	
Exterior shading	fixed horizontal overhangs increasing from north to south in the 0.4–1.1 m range	Bustamante et al., (2009)
Window openings	24-hours average whole-house air-exchange rates increasing from south to north between 5–30 ac/h (from 20:00 to 8:00 hrs)	Bustamante (2001); Müller (2006)

All together the design techniques reviewed suggest that there is an overlooked potential to design dwellings for which thermal comfort can be achieved free-running all year-round. The thermal capacity of buildings should be sufficient to ensure a minimum and maximum indoor temperature that will not require consumption of fuels and within which individual temperature requirements can be adjusted by making changes to the building envelope, for instance, opening and closing windows, using insulated blinds, window vents and external shades. Actual fuel consumption in households and occupant thermal comfort preferences are now debated.

2.4 Evidence from Field Studies

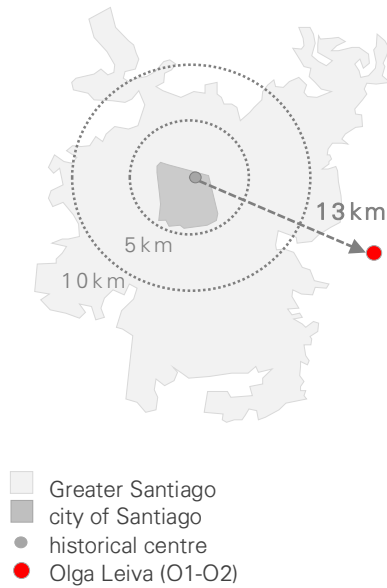
A survey was carried out early in this project to investigate fuel consumption patterns and occupant behaviours regarding the maintenance of indoor thermal comfort. The survey was undertaken during winter 2011 involving data gathered for 200 households from a state housing development built in 2010 at the eastern outskirts of Santiago (**Figure 2.2**). The local climate is characterised by mild winters and summers with average temperatures of 8.4°C in the coldest month (July) and 22°C in warmest (January) and large diurnal temperature variations typically exceeding 10K (see climate chart in Appendix 8.5, Figure 8.4). The dependence on backup energy for space-heating and cooling is relatively low compared to other uses accounting for less than 15% of the annual domestic energy use, 1,200 kWh/m² per household (MINEN, 2010).

The housing scheme meets minimum statutory thermal and standard regulations for public residential dwellings (CTR, 2007). The buildings shown in **Figure 2.2** are grouped into three-storey terraces with 60 m² net habitable floor area and built on a mix of brick masonry and timber-frame constructions complying with maximum thermal transmittances for exposed roof and walls (CTR, 2007), and minimum allowable glazing size per habitable room (HSFP, 2015). As an indication, by considering all assumptions being equal (Appendix 8.5), the space-heating energy use estimated in this study for the intermediate and semi-detached terrace units represent 58–92% of that for a standard detached of Santiago (Figure 2.1), 15–25 kWh/m² annually. Notwithstanding these differences, the income and behavioural characteristics of households were found to also have an influential effect on determining the rate of space-heating energy consumption.

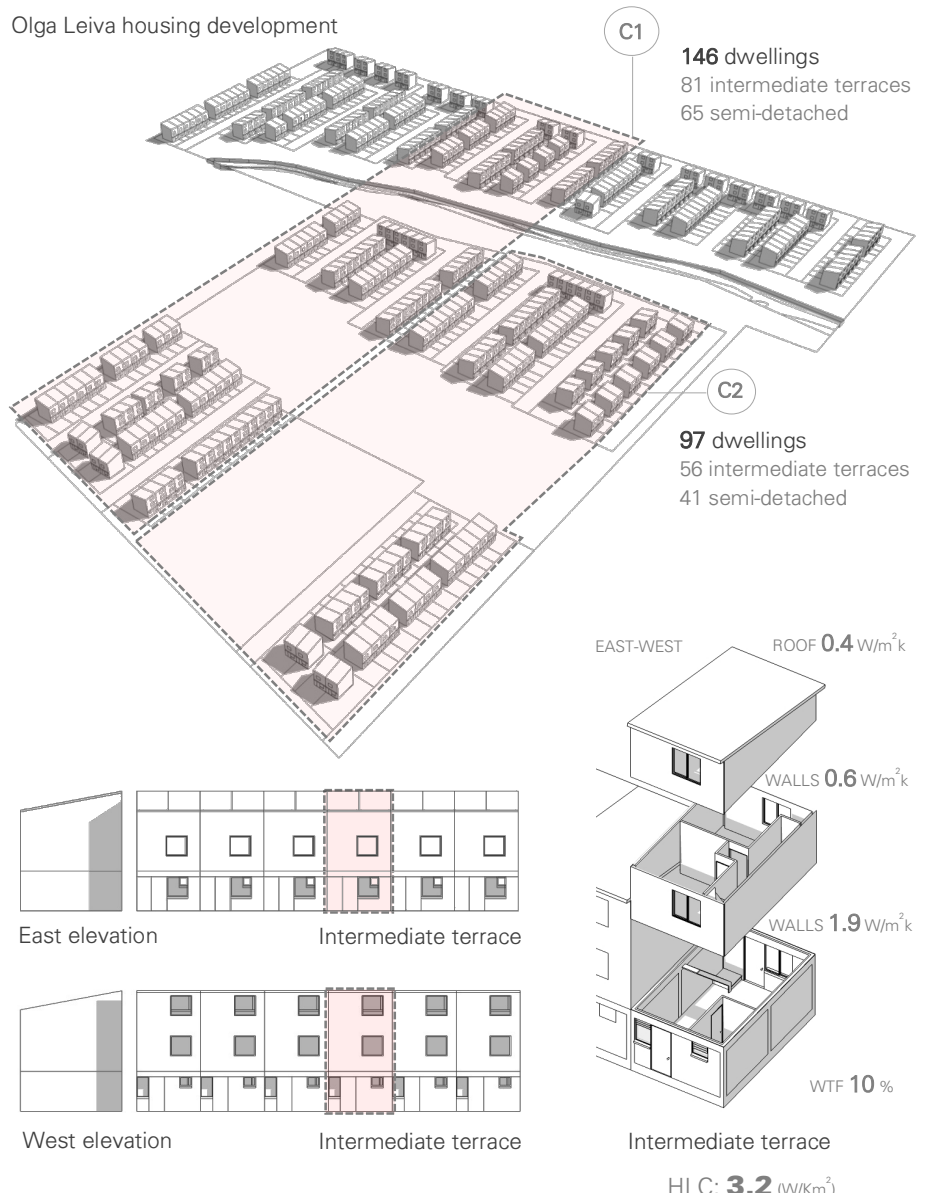
The households surveyed for this project were a mix of low and middle income families (Table 2.4). The household population was composed mostly by families with children (66%) which by allowing overlaps between different groups were followed by: families with elderly (35%) single parents with children (13%) and adult couples (14%), all coming from an informal settlement nearby (Figure 2.2). A relevant characteristic of the households was the proportion of members likely to stay at home during the day (35%), composed mainly by dependants and adult female householders. This last group constituted most of the respondents of the sample (52%) selected randomly as the survey took place (for further procedures and data see field studies instrumentation in Appendix 8.1). The findings of the survey discussed in the following sections were grouped into three interrelated categories:

Figure 2.2 Summary of field studies for a housing development in Santiago

Field studies were undertaken in *Olga Leiva* a large state housing complex of 400 dwellings built for families living in at the eastern Santiago slum of Peñalolen. The households surveyed within the areas highlighted beside (see O1-O2), were from both intermediate and semi-detached terrace units. From the total of households surveyed ($n=200$), 91% were reported to have mechanical space heating and only 5.5% mechanical cooling at the time the studies were carried out.

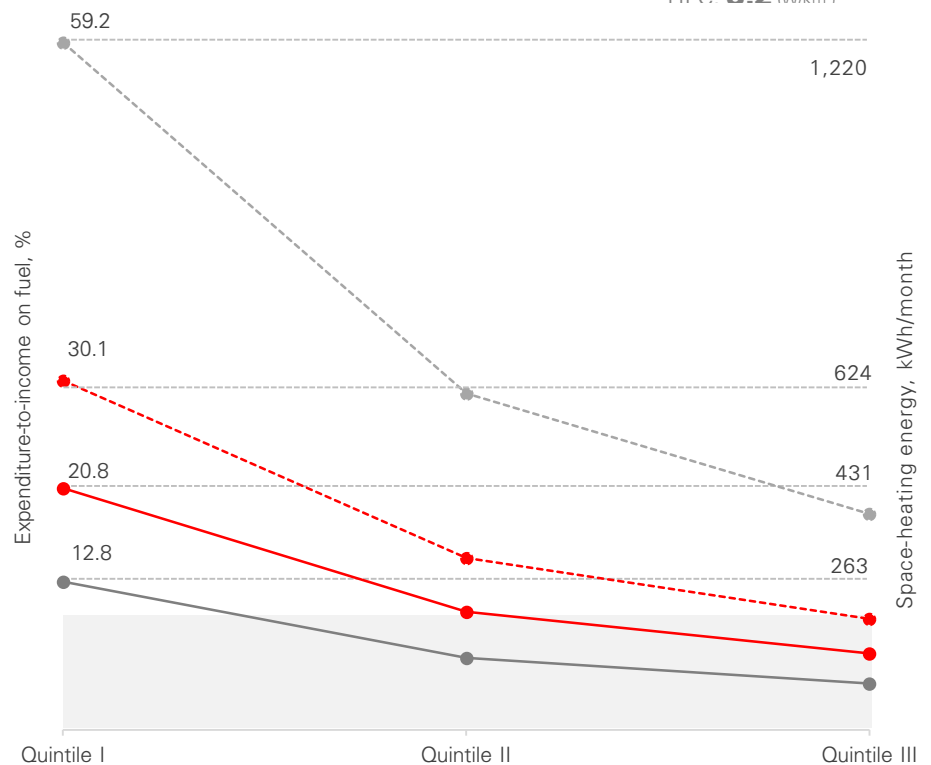
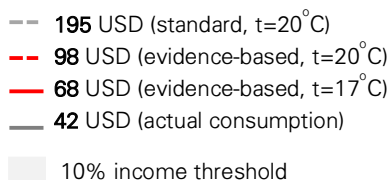


Olga Leiva housing development



2.2a Space heating energy use

The graph compares actual space heating energy use reported in the survey with simulations performed for the intermediate terrace shown beside (see Figure 2.3), the same dwelling where the median poorest household resides (Table 2.4). The *straight grey line*: represents the actual use of fuel for space heating. The *red lines*: are the energy projected for the living area and bedrooms for a 16-hours set-point of 17°C (straight line) and 20°C (broken line). The *dotted grey line*: is the energy estimated for a whole-house 24-hours set-point of 20°C with night-time setback of 17°C (see input data for simulations in Appendix 8.5).



2.4.1 Household Fuel Consumption

The households were asked to report daily fuel consumption practices. Results of capital expenditures, summarised in Table 2.4, confirm that fuel poverty is a prevalent issue among low-income dwellers. At the time of the survey over 80% of the interviewee were in households experiencing financial hardship due to relative high expenditures on fuels. Space-heating accounted for more than half of the monthly fuel consumed by the households for which conventional kerosene (56.5%) and propane gas (38.4%) unvented combustion heaters were used predominantly. Recent laboratory emission testing by the national environment commission indicates that more than 3 hours using these devices may exceed maximum room limits for carbon monoxide (CO), fine particulate matter (PM_{2.5}) and nitrogen dioxide (NO₂) (CONAMA, 2015). In this study, the use of unvented combustion space-heaters were also identified as a major contributor to the poor thermal efficiency of dwellings.

Table 2.4 highlights the inconsistency between actual fuel consumption and conventional predicted energy use (MINVU, 2015). As depicted in the table, the poorest median household spend 12.8% of income on fuels for space-heating. For the same dwelling conditions, the amount of fuel required to provide additional backup space-heating when occupants are awake and unable to maintain their thermal comfort will increase income losses to 21–30%, depending on appliance usage characteristics (Figure 2.2a). The results shown in the figure are quite revealing of the costly efforts required to meet conventional energy predictions which will raise capital losses by as much as 59% of household income. Since too much energy is being accounted for when not required by the occupants, conventional design measures to improve dwelling thermal performance would have negligible effects on the actual thermal comfort conditions experienced by the household.

Table 2.4 Monthly expenditure-to-income on domestic fuels

	<i>Quintile I</i>	<i>Quintile II</i>	<i>Quintile III</i>
	kWh	kWh	kWh
Household fuel consumption	522	800	989
space-heating	263	394	466
electric equipment	117	161	201
water heating and cooking	142	245	322
Expenditure-to-income	21%	16%	13%
expenditure on fuels (USD)	69	108	136
household income (USD)	330	674	1,048

Notes: fuel consumption was derived from capital expenditures reported in the survey with 2011 energy prices for eastern Santiago. See conversion factors for different appliances in Appendix 8.3.

2.4.2 Dwelling Thermal Performance

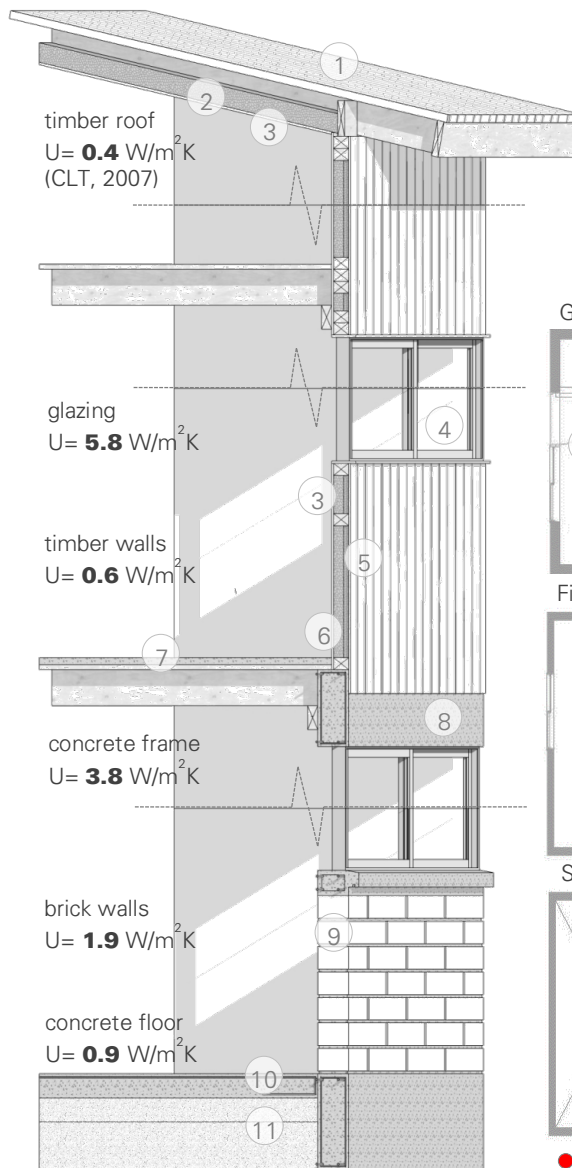
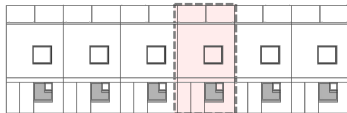
The influence of occupant behaviour and building operation patterns was investigated. Indoor space temperatures were measured in the living area and bedrooms of four terrace dwellings (Figure 2.3). The studies were carried out

Figure 2.3 Results of a monitoring study for terrace dwellings

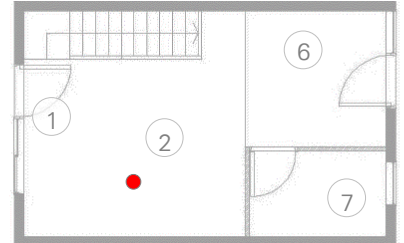
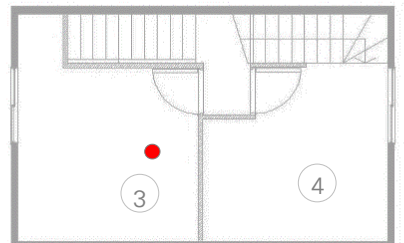
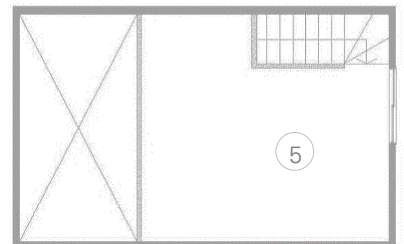
The figure below shows the plan and specifications for an intermediate terrace unit at *Olga leiva* (after UTPCh, 2010). **2.3a** The graph below shows the range of room temperatures (red lines), measured in one of the intermediate terrace unit during a cold and sunny winter week in July (outdoor weather data after SINCA, 2010). The grey bars show the number of occupants, the grey dots show when the space heater is turned on in the living area and the broken line the number of windows opened (see data collection form in Appendix 8.1).

Layer of materials

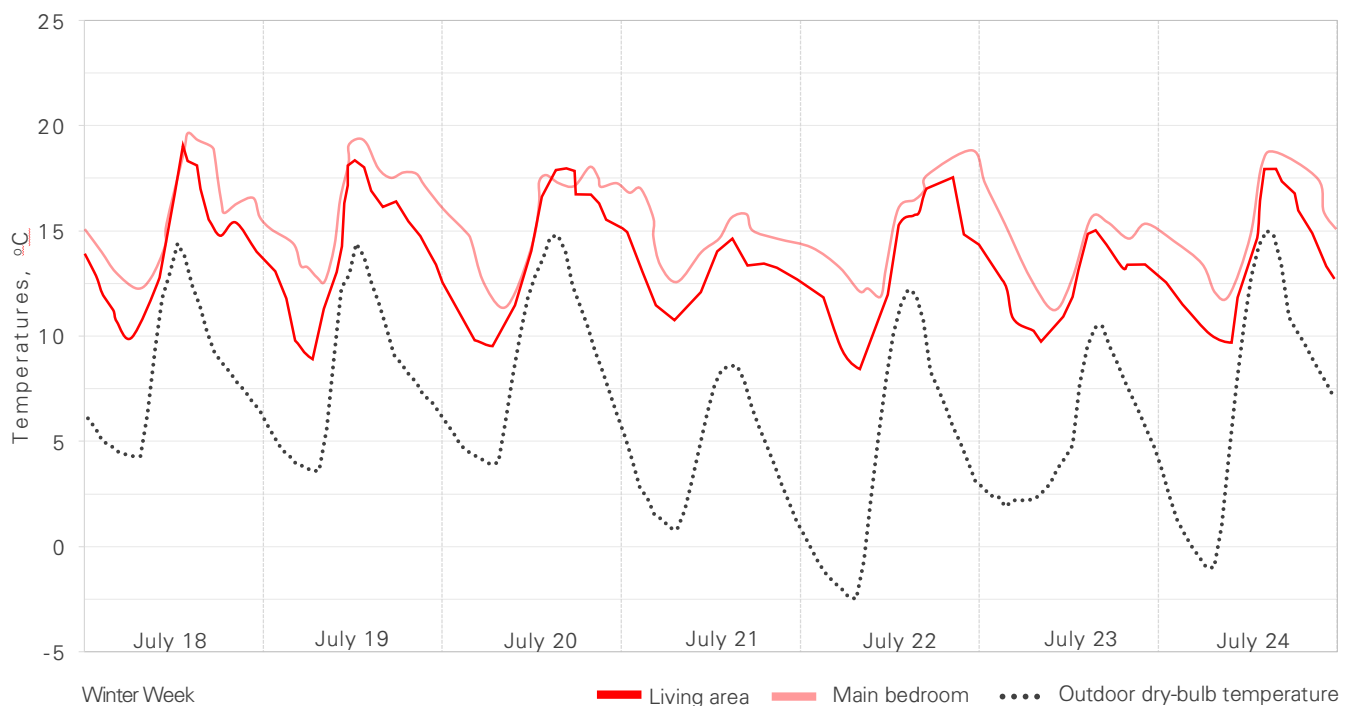
1. asbestos (5mm)
2. insulation EPS (80mm)
3. plasterboard (10mm)
4. clear glass (3mm)
5. OSB panel (11mm)
6. insulation EPS (50mm)
7. plywood board (20mm)
8. concrete frame (154mm)
9. ceramic brick (154mm)
10. concrete (100mm)
11. sand blinding and hardcore

Intermediate terrace**Plan**

1. Access
2. living area (15 m²)
3. main bedroom (11 m²)
4. bedroom 2 (8 m²)
5. bedroom 3 (15 m²)
6. kitchen (5 m²)
7. bathroom (8 m²)

Ground floor**First floor****Second floor**

● position of data-logger



during a typical cold winter week when outdoor temperatures were in the 0–20°C range (SINCA, 2010). As shown in Figure 2.3, maximum occupation take place in the living area during afternoon and evening hours, between 3–10pm, when all family members usually engage in regular domestic activities such as watching TV, child caring, dinning and spending quality time together. Coinciding with the time outdoor temperatures start to drop below 10°C from 5–6pm onwards, evening occupied hours are critical for occupants to maintain adequate indoor thermal comfort conditions.

However, indoor temperatures are below minimum acceptable comfort ranges during most of evening occupied hours. Two distinctive operation patterns can be observed in Figure 2.3. During midday hours, windows are regularly opened by the occupants to remove residual gases from indoor combustion sources (cooking, space-heating) maintaining temperatures virtually coupled with the outdoor. Conversely, during the afternoon when room temperatures drift below 15°C, unvented kerosene and gas space heaters are used to heat occasionally the living area while windows are kept closed. Large indoor temperature swings and combustion emissions explain the intermittent pattern of fuel consumption in dwellings which exposes occupants to a combination of excess low indoor temperatures and toxic pollutant concentrations.

2.4.3 Indoor Temperature Requirements

Further questions were included in the survey to characterise the use of appliances and occupant thermal acceptability. The respondents were asked to provide detailed information about the use of space heating and cooling appliances specifically: ownership, location and extent of operation in dwellings. Indoor temperatures were measured at place while respondents were asked to rate their thermal sensation on a seven-point scale ranging from cold (-3) through neutral (0) to hot (+3) (see detailed procedures in Appendix 8.1). The results of the field measurements are compared with those of surveys carried out for dwellings in Santiago (CNE, 2008, 2010), and predicted comfort temperatures based on latest updates to assessing thermal comfort in residential buildings (see adaptive thermal comfort criteria in Section 3.4).

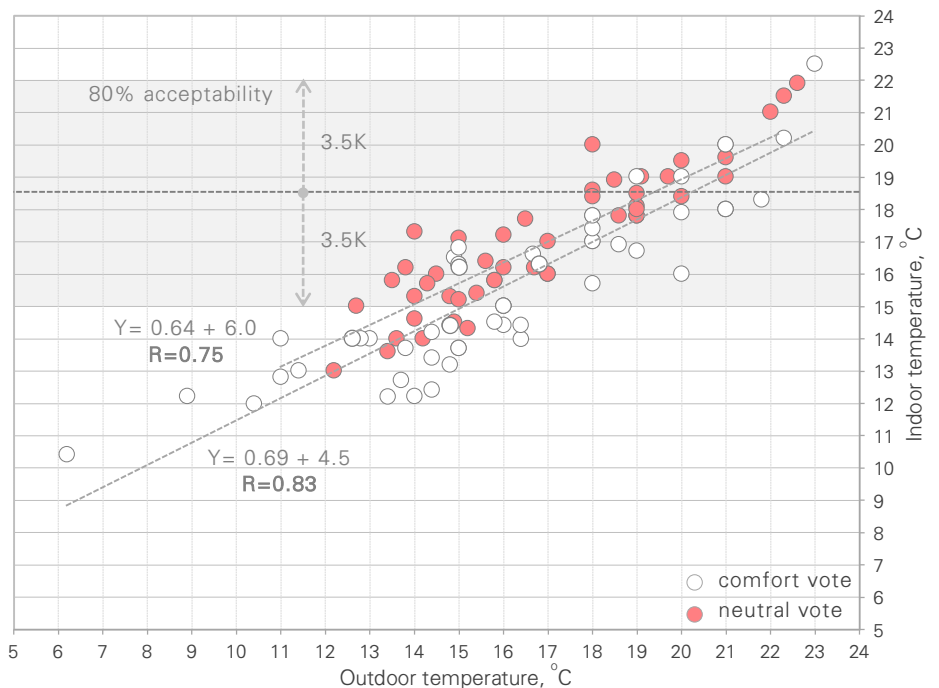
The first set of questions confirmed that space-heating and cooling appliances are rarely used over the year but partially during cold and warm season days. Similar to current consumption patterns reported by the national energy commission for dwellings in Santiago (CNE, 2008, 2010), virtually no mechanical means are used for indoor space-cooling, as less than 6% of the respondents reported to actually have mechanical cooling devices only using them occasionally during the hottest days (Figure 2.2). In turn, as shown in Figures 2.2 and 2.3, individual portable space-heaters are used intermittently throughout cold season days, on average four hours per household. Portable open-flame heaters, with no thermostat settings, are used preferably in the living area and rarely at night or in bedrooms as respondents explain due to fear of poisoning, burns or possible fire hazards.

The evidence indicates that there is a broad range of temperature conditions at which no conventional backup space-heating nor cooling energy is required to achieve occupant thermal comfort. The result of the survey, plot-

ted in **Figure 2.4**, corroborate the broad thermal acceptability of dwelling occupants which resulted between 15–22°C for 80% acceptability, thus within the $\pm 3.5\text{K}$ range when the outdoor mean temperature was 12.9°C. Similar in range but lower in values than the 17–24°C occupant comfort limits predicted for the same outdoor conditions (de Dear 2011; Humphreys et al., 2013). The regression and correlation coefficient obtained in the graph suggest that occupant thermal comfort has a great sensitivity to changes in outdoor temperatures. As well as having relevant implications in contributing to predict energy use, the broad thermal adaptability and active involvement of occupants in maintaining indoor thermal comfort opens a wide range of undervalued operable elements that will contribute to reduce fuel use and pollution emissions in dwellings (Nicol & Humphreys, 2004; Nicol, Humphreys, & Roaf, 2012).

Figure 2.4 Plot of occupant comfort temperatures in dwelling

The dots depicted in the graph are the outdoor and indoor temperature measured at the time the survey was performed for each interviewee at Olga Leiva in winter 2010. The *grey area* indicates where 80% of comfort temperature votes lie and the *broken lines* the regression equations obtained for each group surveyed at the complex (Figure 2.2); the *red dots* are the neutral temperature vote (0) and the *white dots* all votes but neutral, namely from cold (-3) to slightly cool (-1), and from slightly warm (+1) to hot (+3) (some votes overlap between each other).



2.5 Conclusion

The extent and severity of fuel poverty are deeply engrained in the thermal inefficiency of built dwelling stocks. The existing body of research has been limited in identifying the actual behavioural, building technological and design factors influencing thermal comfort and fuel consumption in dwellings. However, findings of field studies carried out in this study indicate that by focusing on occupant thermal comfort and preferences there is promising scope for designing dwellings that can be heated and cooled naturally without recourse to backup energy. Further analysis in the thesis will be undertaken to translate these findings into applicable design techniques that will contribute in developing an enduring means of reducing fuel consumption in dwellings.

¹ For instance, households in which space-conditioning energy appliances are not used because they are not possibly afforded or simply because of choice (CNE & GTZ. (2008b), or households disconnected from national energy supply networks (Cerdeira & Gonz  lez, 2017).

3 Towards a New Housing Strategy

3.1 Introduction

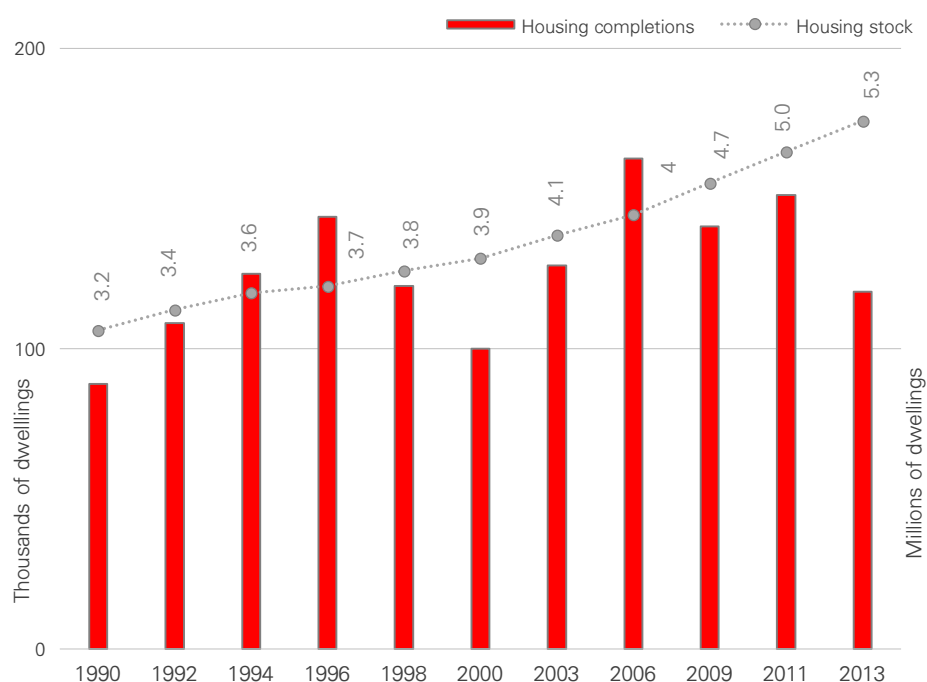
This chapter presents a national strategy for building, delivering and operating naturally conditioned dwellings for application to a range of different locations across Chile. The objective is to reduce current dependence on fossil fuels by expanding the period over the year during which dwellings are operated using free energy sources. Latest knowledge on passive design of buildings is applied to set out a range of dwelling configurations, construction materials and operable envelope elements to improve the thermal performance of standard dwellings —defined as residential buildings that meet standard accommodation characteristics and minimum statutory requirements. Criteria to achieve occupant thermal comfort with minimum or no recourse to extra capital, running and environmental costs are considered.

3.2 Profile of Dwelling Stock

The scope of the strategy is defined by analysis of thermophysical characteristics of dwelling stock. There are currently more than 5 millions of dwellings in Chile, mostly detached, semi-detached and terraces (89%), built on traditional brick and timber-frame constructions before the Chilean thermal regulation (CTR) was introduced in 2000 (CASEN, 2015). However, over the last

Figure 3.1 New dwelling completions, period 1990-2013

New dwelling completions (after INE, 2015) and national dwelling stock per year (after CASEN, 2015). During this period the national stock increased by more than 60%, that is from 3.2 million dwellings in 1990 to 5.3 million dwellings in 2013.



two decades, major demographic transformations changed the dominant form of accommodation and construction (**Figure 3.1, 3.2, 3.3**). Considering the steady expansion of housing stock which grows over one-fourth per decade (INE, 2015), the supply of naturally conditioned dwellings can be a pivotal turn towards the development of an energy self-sufficient housing stock.

The widespread stock of low-density dwellings in suburban areas has placed an urgent need for the state to build compact infill housing accommodations (UTPCh, 2013). This has been partly materialised through an increase in production of apartment dwellings which in the last ten years doubled and became the primary form of accommodation, exceeding over 54% of housing completions in 2015 (**Figure 3.2**). The construction of apartment buildings in inner-city areas is financed by the government to attract low-income dwellers back from suburbs, reduce commuting costs and improve access to public services (OECD, 2013). However, the high relative costs of inner-city land and infill apartment construction are excluding low-income dwellers to live in city centres which is increasingly being demonstrated by planners and developers to improve access to job, education and socioeconomic opportunities (Celhay & Sanhueza, 2011; Gatica, 2011; López, 2015).

The construction of concrete residential apartments and the changes in building thermal regulations are transforming the construction industry. While concrete became the predominant structural wall material used in dwellings, displacing brick masonry (**Figure 3.3**), several alternatives have been introduced to improve the thermal insulation of building envelopes, for instance, lightweight insulated timber and concrete panels and blocks (DITEC-MINVU, 2014). The rise in use of concrete followed its increasing demand in the private sector to build apartment buildings of 9 storeys and higher (**Figure 3.4**). The development of public inner-city housing requires innovative construction methods for flexible assembly of apartment dwellings, reduce time and on-site impacts of construction (pollution, solid waste, and noise), and meet increasingly demanding regulations to improve the energy efficiency and seismic performance of multi-storey apartment buildings (OGUC, 2015).

To account for these emerging trends in housing development, the focus of the strategy is on improving the thermal performance of new standard dwelling designs using conventional and alternative constructions for assembly of multi-unit dwelling and apartment configurations. Criteria for designing dwellings in the context of current affordable housing provision across different regions of the country are discussed in the following section.

3.2.1 Scope and Criteria of Analysis

The assessment of the technical and economic viability of the strategy is limited to analysis of new standard dwellings specified to meet minimum statutory regulations (OGUC, 2015). Household user eligibility criteria, construction specifications, building standards and envelope thermal regulations applied by the government for supply of affordable dwellings are used to define a reference household profile, target construction costs and a range of representative climate locations to perform extensive parametric simulation analysis on improving the thermal performance of dwellings.

Figure 3.2 New dwelling completions, by dwelling type, period 2005-2015

During this period the construction of apartment dwellings increased by over 100%, that is from 42,000 units (29% of stock) in 2005 to 89,000 units (54% of stock) in 2015 (after INE, 2015).

■ Apartments
 ■ Terraces
 ■ Semi detached
 ■ Detached

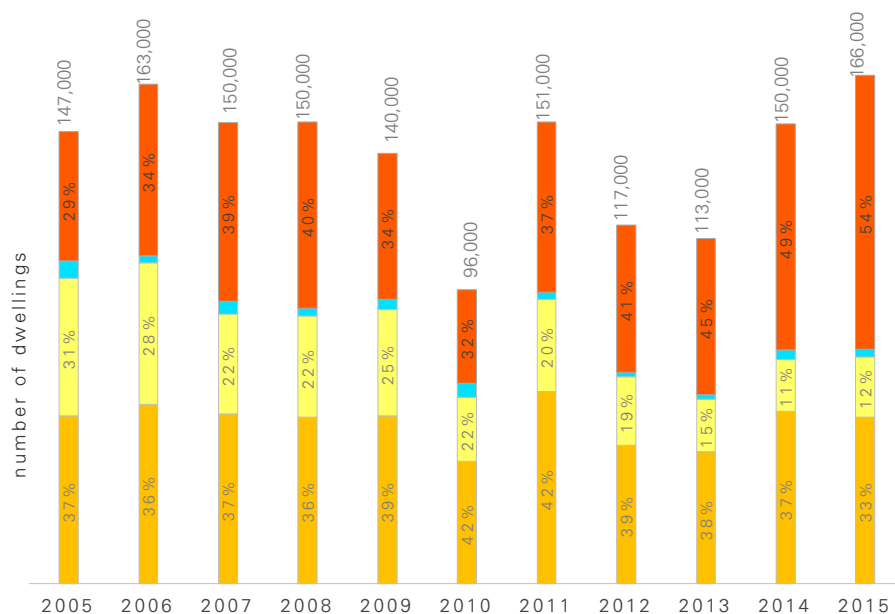


Figure 3.3 New dwelling completions, by building material, period 2005-2015

In tandem with the rise in construction of apartments, the use of concrete for structural wall increased by more than 100%, that is from 44,000 units (29% of stock) in 2005 to 88,000 units (53% of stock) in 2015 (after INE, 2015).

■ Brick
 ■ Other Constructions
 ■ Concrete Blocks
 ■ Timber
 ■ Concrete

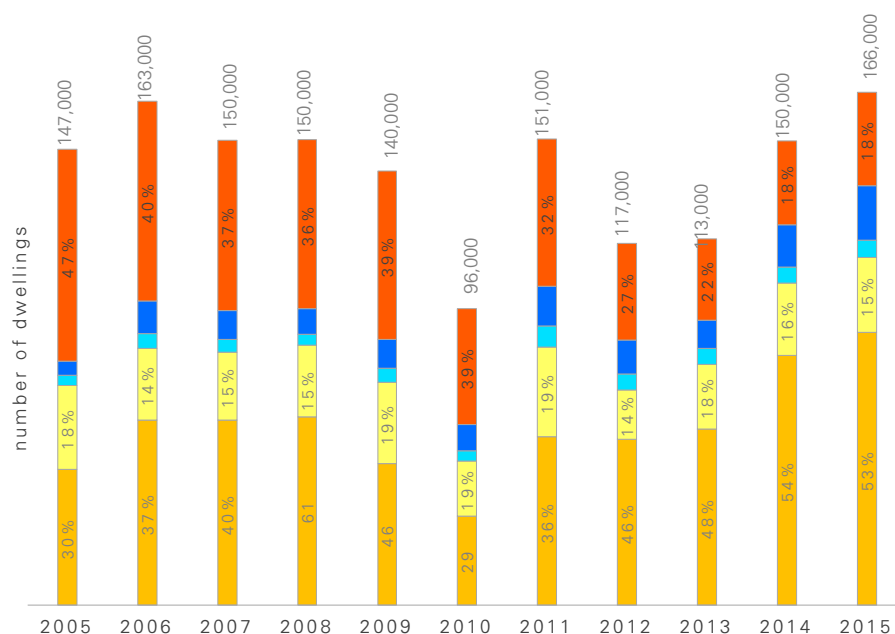
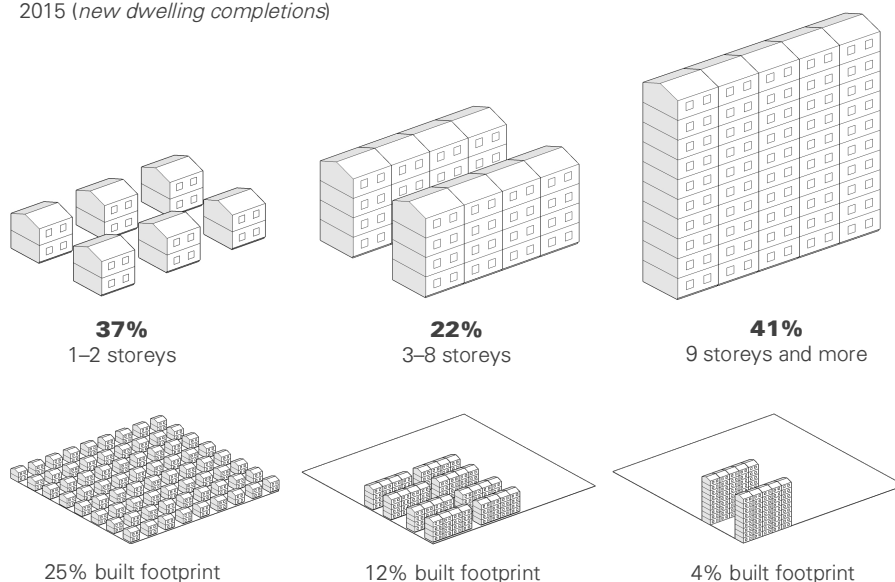


Figure 3.4 New dwelling completions by number of storeys, 2015

More than 89% of the national dwelling stock are low density dwellings of one and two storeys (CASEN, 2015). During 2005-15 the number of completions in high-rise apartment buildings of over 9 storeys increased from 23% to 41% (INE, 2015). These are typically built on reinforced concrete and are highly unpopular characterised as being unaffordable, having lack of privacy, little space and as having poor thermal and environmental conditions (MINVU, 2014).

2015 (new dwelling completions)



Dwelling users: are defined using criteria set by the Housing Solidarity Fund Program (HSFP). This subsidy scheme is run by the ministry of housing and urbanism (MINVU, 2011) to finance the construction of dwellings for families in the three poorest quintiles of income. As shown in **Table 3.1**, the subject household group considered for analysis and setting target design criteria comprise more than 60% of Chilean population, approximately over 3 millions of households (CASEN, 2013). The thermal performance of dwellings is assessed through simulations by using a reference occupancy pattern set from representative characteristics of the subject population by family composition, number of members and monthly income (see reference occupancy and energy use profiles in Tables 3.3 and 3.4 in the last section).

Table 3.1 Dwelling stock by family type and median capital income

<i>Household type</i>	<i>Quintile I</i>	<i>Quintile II</i>	<i>Quintile III</i>	<i>Number of dwellings</i>
Single occupant	9.3%	9.2%	8.6%	288,917
Couple occupants	11.3%	11.8%	13%	634,561
Families with children (18–)	79.7%	71.6%	59.3%	2,346,867
Families with elderly (60+)	31.3%	31.3%	31.3%	1,155,342
Monthly median income (USD)	287	662	973	3,270,345

Note: *subgroups overlap between each other (after CASEN 2013)

According to latest data by the national socioeconomic survey (CASEN, 2013), the largest household group are families with children accounting for over three fifth of the subject population (Table 3.1). These households which are primarily working age couples with school-age dependents are chosen as reference for building simulations considering the population average of four members per household (CASEN, 2013) (research beyond this study will be required to compare the effect of variations in occupancy). The reference profile of occupation is set for a typical family composition by activity status consisting of one adult in full-time employment, one adult who stay at home to care for the house and two children in full-time education (MIDEPLAN, 2013).

Household income: data used as reference for assessing the effects of improving building thermal performance and reducing energy use on monthly capital income of households was retrieved by region from median income figures sorted by national income quintiles from CASEN (2013).

Construction costs: are set to comply with capital budget allocated by the HSFP. This is defined for a maximum of 50,000 USD, per household, to cover all housing costs including: site preparation, building construction, finishes, services and exterior amenities (MINVU, 2011). The economic assessment of the strategy focuses on capital costs of building construction and finishes starting from 15,000 USD per dwelling, estimated for multi-unit residential developments (Appendix 8.3). Extra capital investments to improve the thermal performance of dwellings are considered to weigh benefits of reducing energy consumption, using the following equation:

$$NPV = \sum_{t=1}^T \frac{COST_{E,t}}{(1 + sdr)^t} \quad (3.1)$$

where NPV = net present value, USD
 COST_E = extra capital investment, USD
 COST_P = present cost of energy, USD
 sdr = social discount rate
 t = period of analysis

Energy consumption costs: in dwellings are estimated for present and future energy prices to final household users. Current fuel prices are obtained from data by the national consumer service (SERNAC, 2016), and future fuel prices are derived from historical time-series prepared by the national energy commission, period 1990-2015 (CNE, 2016). Following criteria by the HSFP for economic evaluation of public projects the time horizon for appraisal of capital investments was set at 30 years with a social discount rate of 6% (MIDEPLAN, 2013). The present cost of energy is estimated as follows:

$$COST_{E4} = \sum_{t=1}^t \left[\frac{E \times COST_F}{\eta} \right] \times h \quad (3.2)$$

where, COST_{E2} = present cost of energy, USD
 E₄ = energy consumption, kWh
 η₄ = efficiency of appliance
 COST_{F4} = present cost of purchased fuel, USD/kWh
 h₄ = hours of operation

Locations of study: are chosen to comprise a representative sample in terms of dwelling performance and outdoor climate characteristics. Although Chile has a wide array of climates ranging from hot to cold extremes (**Table 3.2**), most of its dwelling stock is distributed along its northern coast and central southern regions dominated by mild temperate climates (INN, 2008), and accounting for more than 85% of the total national housing stock (CASEN, 2015) (see outdoor weather data by location in Appendix 8.5). As shown from the results of simulations in Figure 3.5, the thermal performance of dwellings

Table 3.2 Dwelling stock by natural region and climate zone

Natural Region	Climate zone	Number of dwellings		Location	Met station	°S	°W
Northern Chile	North Dessert	58,170	1%	Calama	El Loa	20	69
	North Valleys	136,856	3%	Copiapó	Chamónates	26	70
	North Coast	397,330	8%	Antofagasta	Antofagasta	23	70
Central Chile	Central Coast	307,042	6%	Valparaíso	Valparaíso	33	72
	Central Interior	2,923,072	55%	Santiago	Pudahuel	33	71
Southern Chile	South Interior	565,407	11%	Temuco	Maquehue	37	73
	South Coast	682,117	12%	Puerto Montt	El Tepu	41	73
Austral Chile	South Extreme	142,921	3%	Punta Arenas	Punta Arenas	53	71
Andean Range	Andean Range	69,087	1%	-	-	-	-

Sources: natural regions from CORFO (1966); climate zones from NCh-1079, INN (2008); dwelling stock from CASEN (2015); met stations from Meteotest (2016).

Figure 3.5 Regional variations in heat loss coefficient for standard base-case dwellings

Variation in heat loss coefficient (HLC), for a base-case (or reference case for the purpose of comparison) a 70 m² single-storey detached house built on timber-frame constructions, complying with minimum statutory requirements: maximum thermal transmittance (U-value), by location, for roof and walls, and 10% window-to-floor area single-glazing ($U=5.8 \text{ W/m}^2\text{K}$) and 1.0 ach infiltration rate constant for all locations. The graph shows regional variations in mean daily outdoor and indoor temperatures ($MT_{o,i}$) and diurnal temperature ranges ($DTR_{o,i}$) for typical days selected from hourly yearly data sets from Meteonorm (Meteotest, 2016). Space-heating energy is estimated for the living area and bedrooms for a 16-hours set-point of 17°C, from May to September (see detailed inputs for simulations in Appendix 8.5).

Natural regions

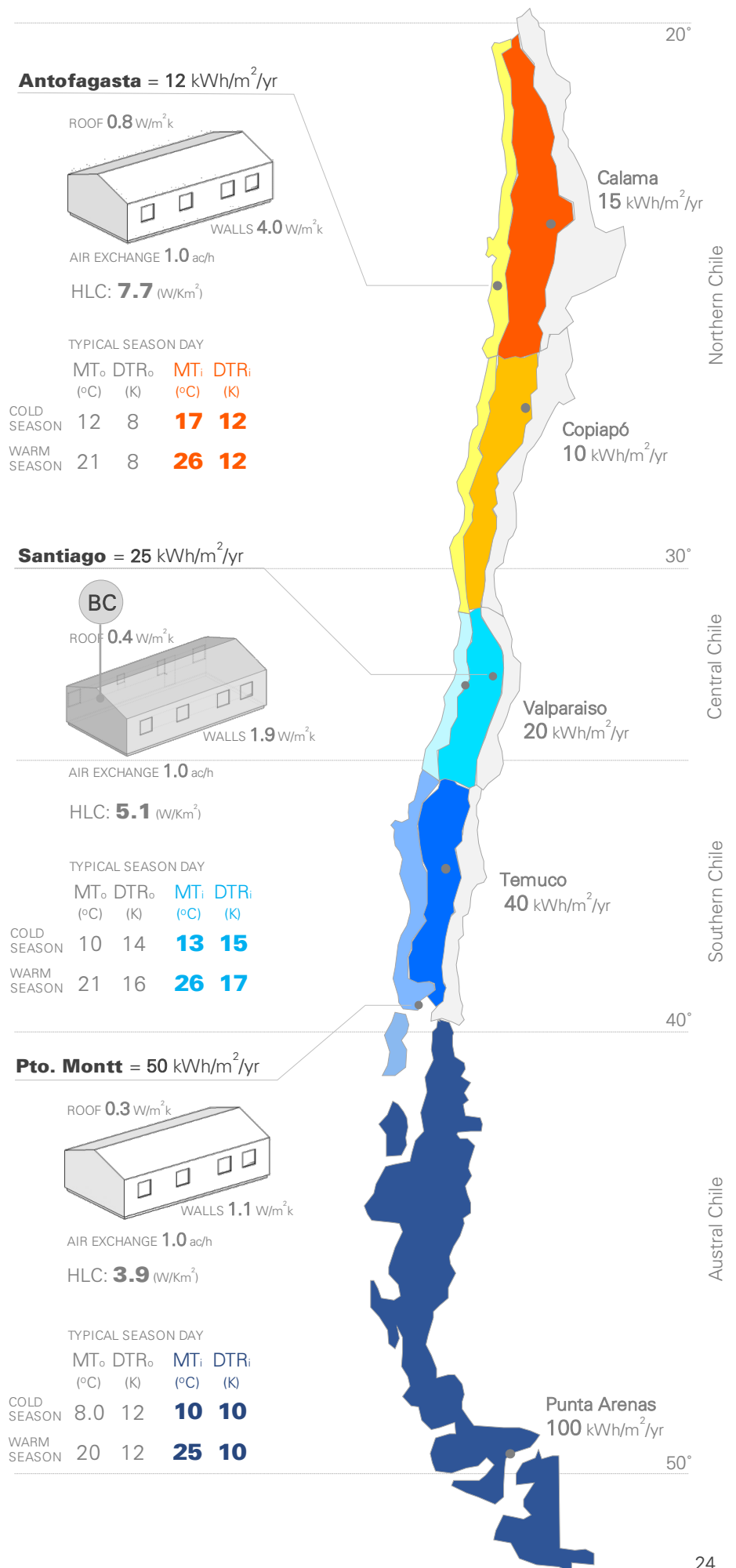
Grey horizontal broken lines (after CORFO, 1966):

- Northern Chile (20–30°S)
- Central Chile (30–35°S)
- Southern Chile (35–40°S)
- Austral Chile (40–50°S)
- Andean range

Climate zones

Residential climate zones defined by standard NCh-1079 (Of.2008):

- Northern Dessert
- Northern Valleys
- Northern Coast
- Central Valleys
- Central Coast
- Southern Coast
- Southern Valleys
- South Extreme
- Andean Range



specified to current statutory regulations (CTR, 2007), varies as a function of latitude along the Pacific shore and longitude between coastal and inland locations. In fact, it can be noted that variations in space-heating energy are larger between nearby coastal and inland locations than over large latitudinal distances across the country.

The main inhabited region of the country is characterised by moderate seasonal but large diurnal variations in outdoor climate conditions (INN, 2008). As shown in Figure 3.5, differences in dwelling thermal performance are explained by moderate variations in mean diurnal outdoor temperatures (MT_o), which decrease from north to south gradually, and by contrast marked differences in outdoor diurnal temperature ranges (DTR_o), between the interior and the coast. A detailed analysis of the influence of outdoor climate on dwelling design is undertaken in the next chapter (see also climate charts in Appendix 8.5, Figure 8.4). To consider variations in dwelling performance and cover an ample section of population, distributed by climate zone in Table 3.2, the locations selected for undertaking extensive parametric simulation analysis are Santiago in the Central Interior (55%), followed by Antofagasta in the Northern Coast (8%), and Puerto Montt in the Southern Coast (12%).

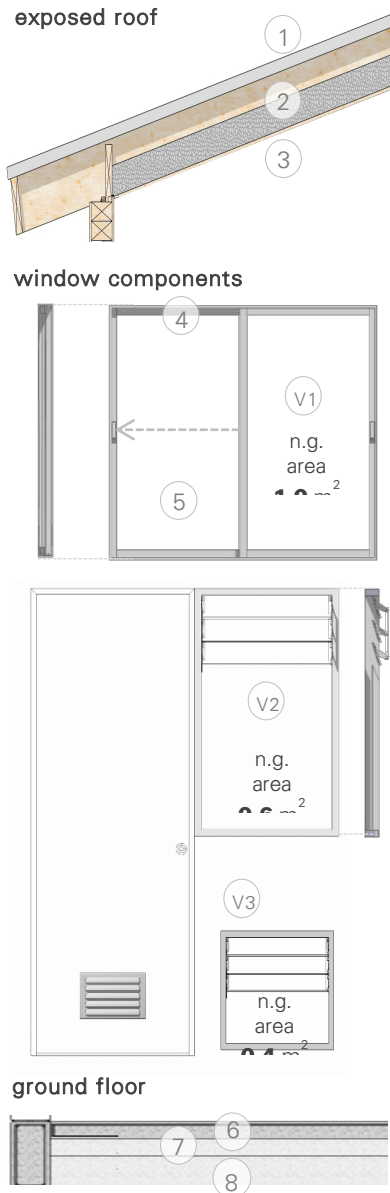
The range of dwelling configurations and building constructions for application of the strategy draws on the performance of base-case dwellings. As shown in **Figure 3.5** for the three chosen locations, during typical cold and warm season days, the mean indoor temperature (MT_i) of the base-case defined as a standard detached house of lightweight timber-frame construction and minimum glazing size is 10–25°C with diurnal temperature ranges (DTR_i) ranging 10–15K. Two main areas of improvements were identified to achieve acceptable indoor thermal comfort conditions: first, specification of appropriate envelope construction materials and glazing properties to narrow diurnal temperature ranges to around 5K and contribute during the cold season to raise mean indoor temperatures by 7K; and second, design of operable envelope components for control of additional excess heat losses and gains. The analytical procedures and design considerations to achieve thermal comfort throughout the year are explained in the following sections.

3.3 Dwelling Configurations and Constructions

Alternatives for design of multi-unit residential developments are considered from single-storey detached to multi-storey apartment buildings. Variations in envelope heat losses by dwelling type in Figure 3.8 indicate that apartments offer significant advantages over traditional low-density housing. The graph shows that for the same number of dwellings ($n=15$) reduction in heat-losses from detached to apartment raises mean indoor temperatures up to 4K saving over three-fourth of the total amount of external envelope insulation required, per development, to meet national regulations (see quantification in Appendix 8.3). Although multi-unit apartment buildings allow for considerable reductions in square meters of building materials, over a number of storeys their costs result higher than houses due to additional requirements for elevators and concrete reinforcement (OGUC, 2015).

Figure 3.6 Standard base-case dwelling: building element specifications.

The thicknesses of insulation for exposed walls and roof of the base-case dwelling are specified to meet maximum thermal transmittance values by location (the values on the figure are based on requirements for Santiago).



Layer of material

1. fibre-cement board (5mm)
2. insulation EPS (80mm)
3. plasterboard (10mm)
4. aluminium casement window
5. clear glass (3mm)
6. reinforced concrete (100mm)
7. Polythene vapour barrier (3mm)

Most of the existing dwelling stock in the country is built on traditional ceramic hollow brick, lightweight timber-frame and reinforced concrete structures (CASEN, 2015). However, the analysis in Figures 3.9 to 3.12 show that traditional constructions require a number of additional measures to meet satisfactory levels of thermal insulation and heat-storage capacity (3.10 and 3.11). To broaden the range of improvements newly available timber panel systems were included in the analysis, namely, a cross-laminated timber (CLT) and structural insulated panel (SIP) (Figure 3.9). Interestingly, as shown in the figure, the CLT panel combines the highest insulation value per unit thickness and enough thermal capacity to maintain acceptable diurnal temperature ranges whereas in turn the SIP panels are among the cheapest (Figure 3.12). Moreover, the use of timber as a construction material has several

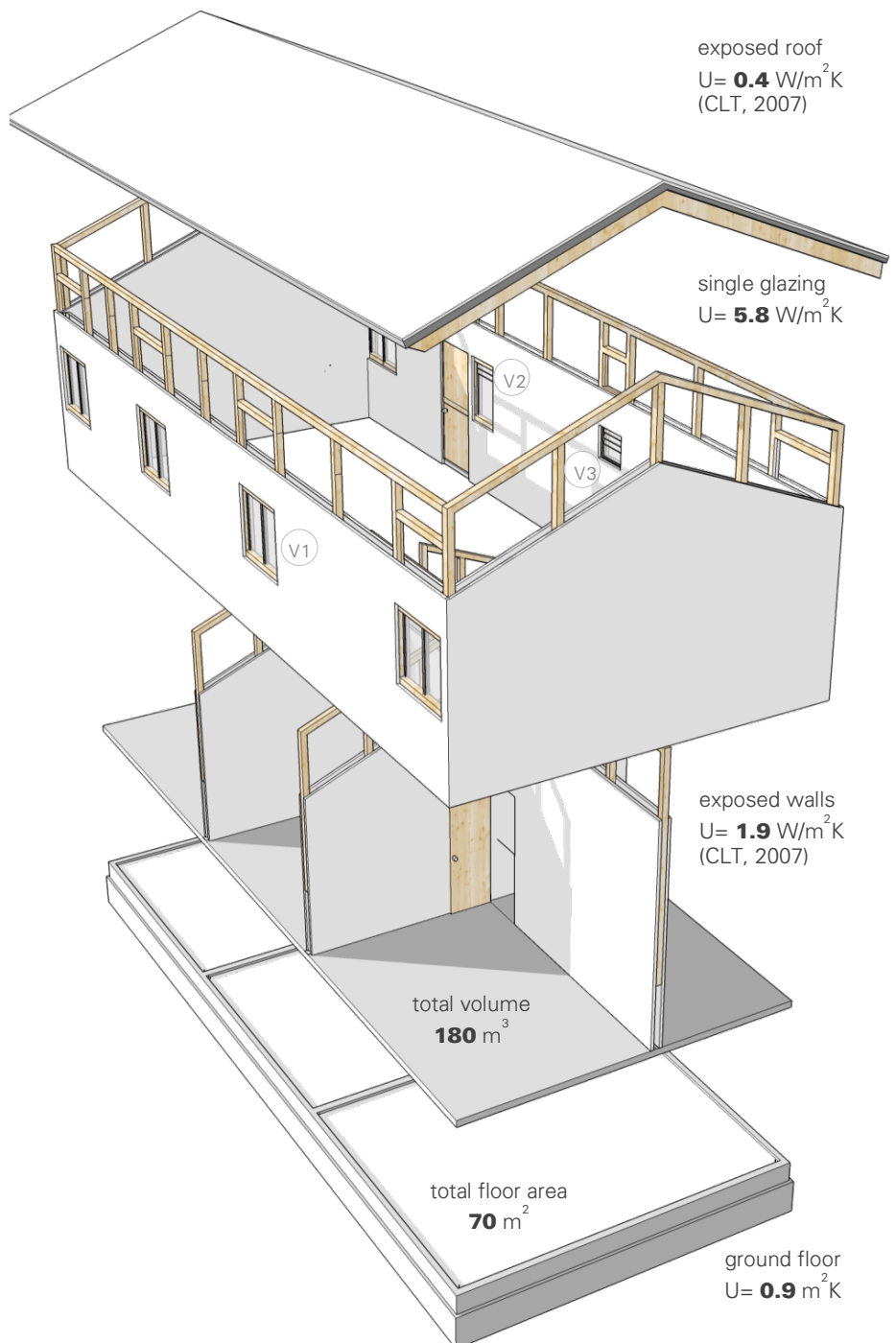
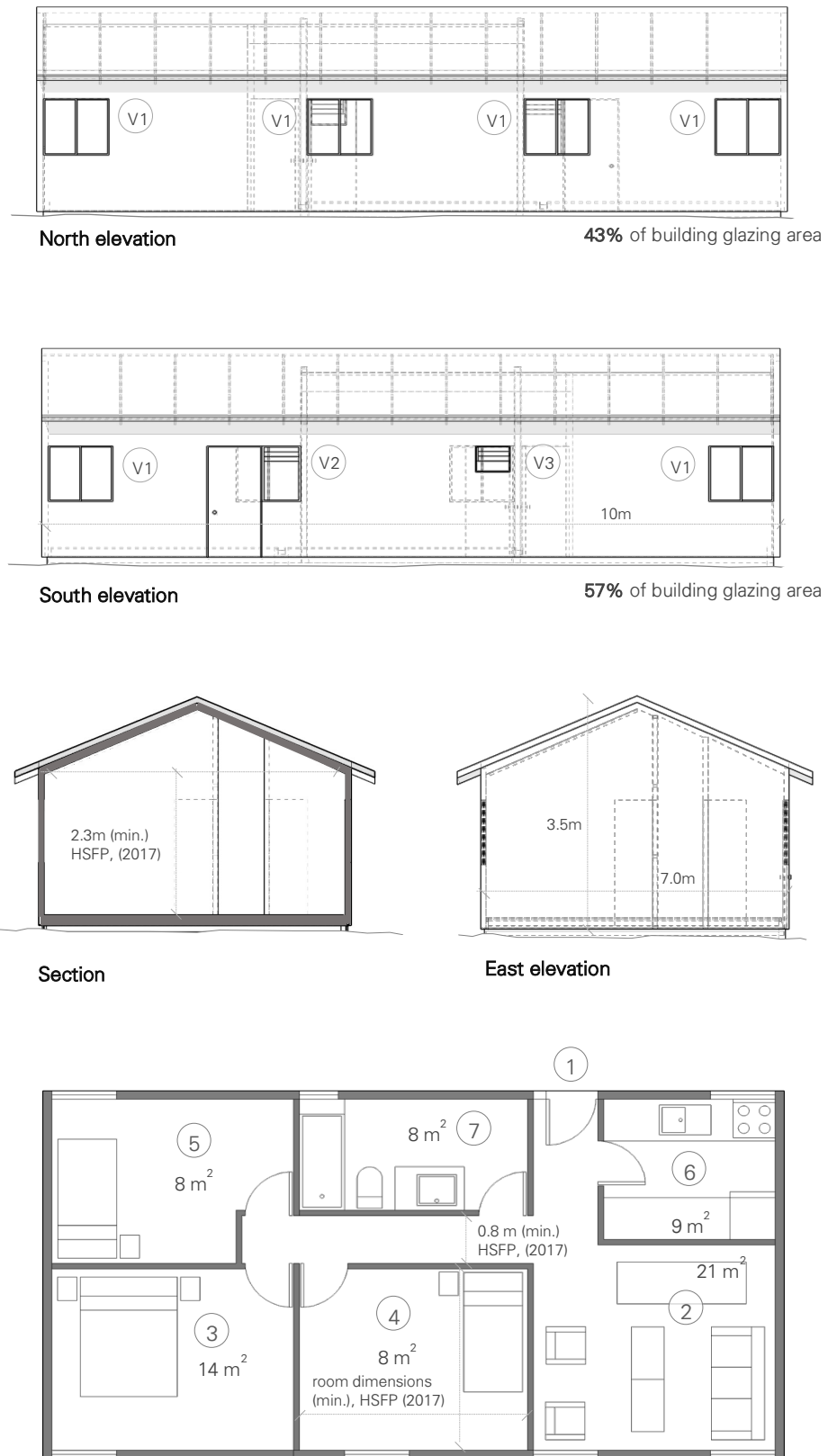


Figure 3.7 Standard base-case dwelling: plan, section and elevations

The base-case was designed to meet different multi-unit configuration types specifically: detached, semi-detached, terrace and multi-unit apartment buildings. Room height, floor area and window requirements for daylighting and ventilation comply with technical specifications applying to dwellings built under the HSFP (2017).



other advantages are just being realised by researchers as ideal for urban infill development as prefabricated timber materials are lighter than concrete (CLT-Chile, 2015), can be digitally fabricated and manufactured off-site improving design flexibility, speed of assembly and reducing on-site impacts such as transport, noise and dust (Weihestephane, 2011; Lehman 2013; Cambiaso & Pietrasanta, 2014).

The technical characteristics of the base-case dwelling in Figures 3.6 were derived from different sources to accord with new national dwelling design standards and current statutory building regulations (OGUC, 2015). The internal distribution of the base-case was drawn from a database of standard housing projects approved by the ministry of housing (MINVU, 2016) and adjusted accordingly to meet typical characteristics of new dwelling stock, specifically: average floor area, number of bedrooms, and predominant envelope assemblies for roof, wall and floor elements (INE, 2015). The design specifications of the base-case in **Figures 3.6** and **3.7** comply with maximum envelope thermal transmittance for exposed roof and walls (CTR, 2007), as well as minimum floor areas, height and widths for habitable rooms (HSFP, 2015).

Variations of the standard base-case performed for undertaking extensive simulation analysis were the most and least exposed dwelling types, the single-storey detached (T1) and intermediate-floor apartment (T5). The graph showing dwelling heat losses in **Figure 3.8** is based on fixed glazing area and minimum statutory envelope insulation for Santiago (CLT, 2007). It can be observed that the variation in the rate of envelope heat-loss per unit floor area is in the order of 3:5 between the two extremes of the graph represented by the detached and intermediate-floor flat respectively. All space-heating operation and thermostat settings being equal, the variation in space-heating energy is in the same order (see regional variations by dwelling type in Table 4.3).

Building envelope constructions considered for analysis include: cross-laminated timber (C1) and structural insulated panels (C2), as well as standard timber-frame (C3), reinforced concrete (C4), solid-clay (C5), and hollow ceramic brick (C6) (see simulation analysis in Appendix 8.5). The graphs in Figure 3.9 compare different properties of building envelope constructions to be taken into consideration for achieving indoor thermal comfort. There are several combinations of building materials that can be applied depending on outdoor weather conditions, comfort design temperatures and building costs. As an indication, differences in mean indoor diurnal temperatures (MTi) between the least and most thermally insulated construction type in **Figure 3.10**, SIP and concrete walls respectively result in the order of 5K whereas differences in indoor diurnal temperature ranges (DTRi) in **Figure 3.11** can reach as much as 10K when comparing a solid-clay brick with a standard timber-frame wall.

3.4 Environmental Design Requirements

Design strategies for assisting occupants of naturally conditioned dwellings in maintaining comfortable indoor environments are discussed. Occupancy patterns and comfort temperature ranges are characterised for design of operable envelope elements that can be adjusted to passively heat and cool premises in response to changes in outdoor climate conditions. The resultant data

Figure 3.8 Heat-loss through building envelope as a function of dwelling type

Variation in heat loss by dwelling type for the base-case, reference dwelling specified on typical timber-frame construction and meeting minimum statutory requirements: maximum thermal transmittance for roof and walls (based on requirements for Santiago) single glazing ($U=5.8 \text{ W/m}^2\text{K}$) and 1.0 ach infiltration (all variables are kept fixed for all dwelling types but the degree of detachment). Space heating energy is estimated for the living area and bedrooms for a 16-hour set-point of 17°C , from May to September (see input data for simulations in Appendix 8.5)

Mean indoor temperature, MTi

(based on results of simulations)

- T1. detached house (13°C)
- T2. semi-detached house (13°C)
- T3. terrace house (14°C)
- T4. upper-floor flat (14°C)
- T5. intermediate-floor flat (17°C)

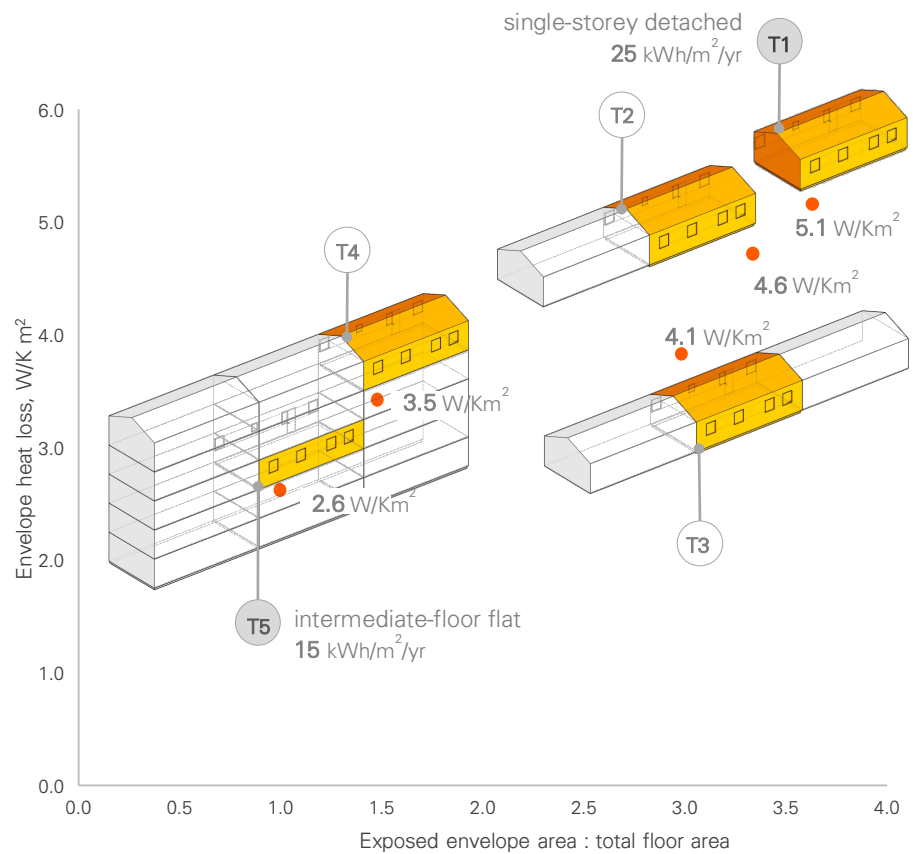


Figure 3.9 Wall construction assemblies used for simulations

Specifications for each assembly used in Figures 3.10, 3.11 and 3.12 are based on technical guidelines prepared by the ministry of housing for designers and builders (MINVU, 2007). The properties of materials are drawn from Chilean standard NCh-853 (INN, 2008) (see respective input data for simulations in Appendix 8.5).

Wall assemblies

- C1. cross-laminated timber (CLT)
- C2. structural insulated panel (SIP)
- C3. standard timber frame wall
- C4. reinforced concrete
- C5. solid-clay brick
- C6. ceramic hollow brick

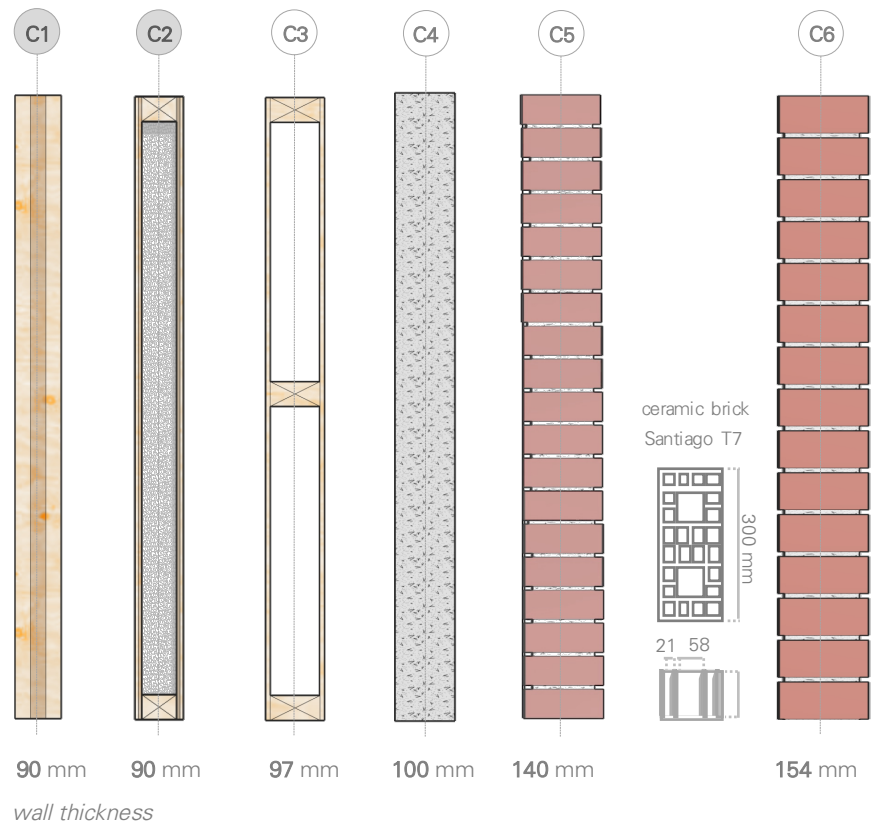


Figure 3.10 Thermal insulation of wall construction assemblies

The graph shows U-values for different wall constructions (without finishes or insulation). The horizontal broken line is the maximum allowable thermal transmittance value for exposed walls in Santiago (CTR, 2007).

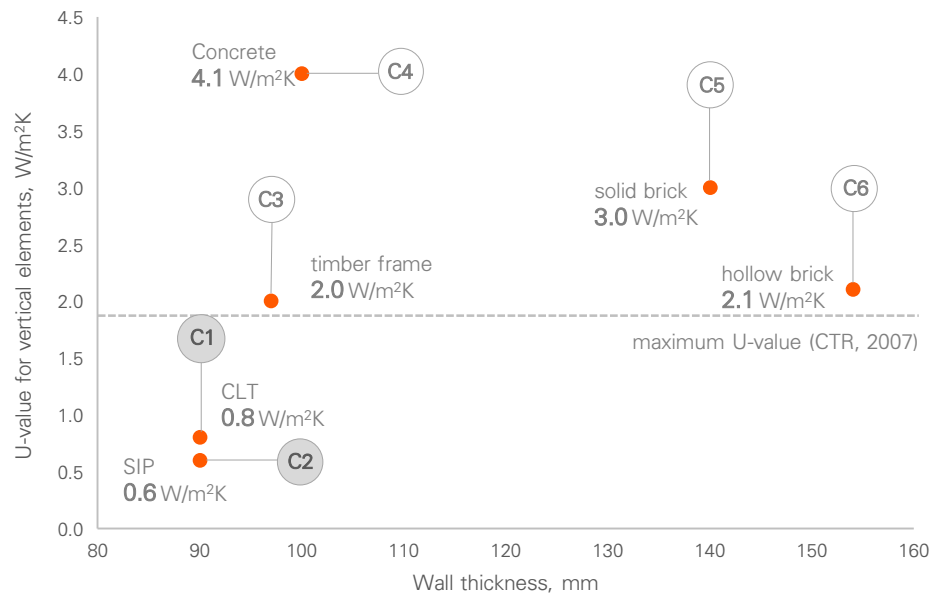


Figure 3.11 Thermal capacity of wall construction assemblies

Effect of different wall envelope constructions on indoor diurnal temperature ranges (DTR_i), based on specifications defined for the base case dwelling for Santiago (see inputs for simulations in Appendix 8.5).

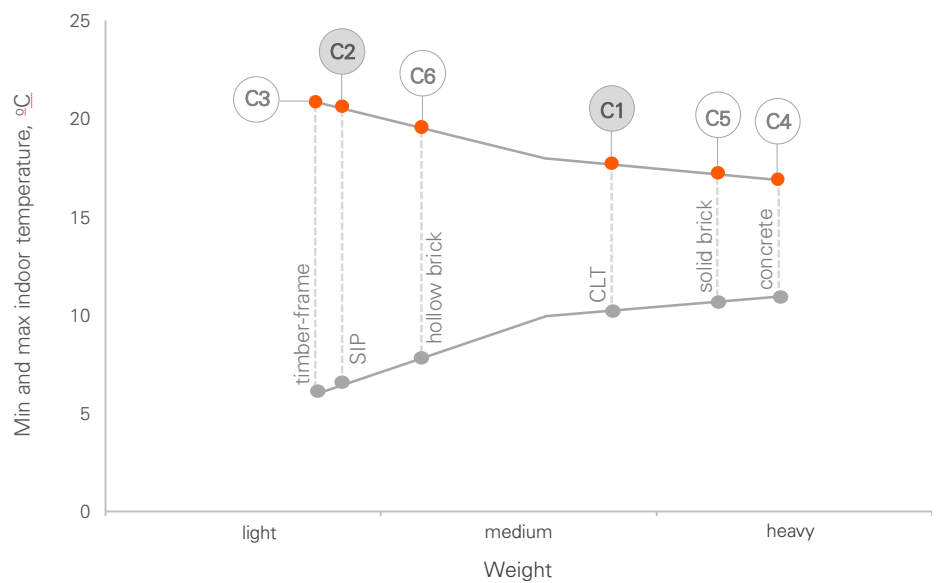
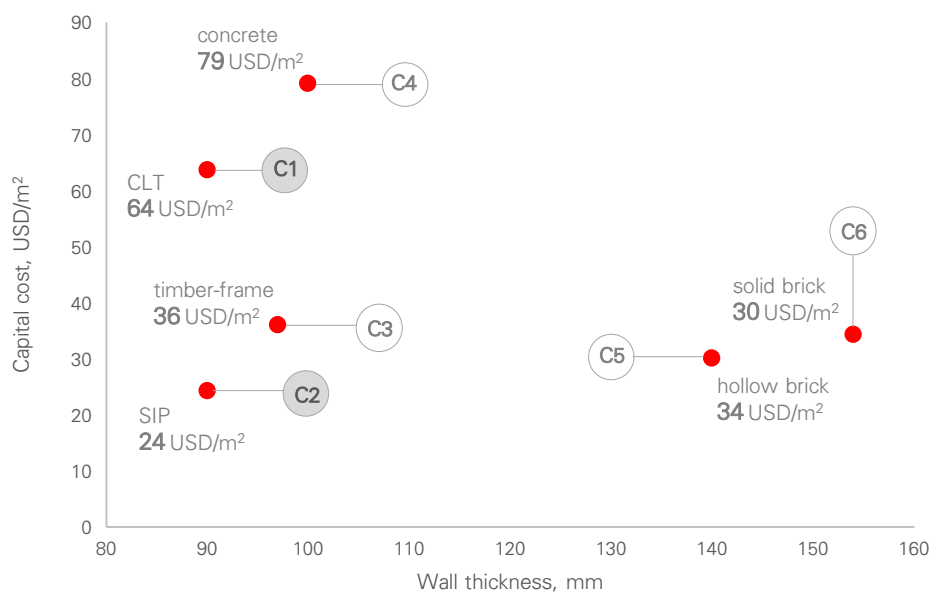


Figure 3.12 Capital cost of wall construction assemblies per square meter

The building capital cost for each assembly is estimated based on current market prices by local manufacturers and suppliers (see sources and unitary construction costs in Appendix 8.3).



is translated into computational input parameters for performing thermal simulations (see detailed input data in appendix 8.5). Provisions of outside fresh air and natural daylight are also considered for improving occupant thermal comfort without compromising indoor environmental quality.

A reference occupancy profile for a household user of four, two adults and two dependents, are summarised in **Table 3.3** (see diversity of household users by composition in Section 3.2.1). Dwellings are assumed under continuous occupation by part of the household: one adult engaged in housekeeping activities staying at home, two children out at school and one adult out at work most of the time (see effects of varying occupancy on dwelling performance in Figure 8.6, Appendix 8.5). Flexible planning and design is required to accommodate activities and allow control of heat losses and gains which vary considerably over time and between households. Special design considerations should be given for control of temperatures in the living area where comfort requirements are likely to change within small timescales and expectations are generally high (Peeters & de Dear, 2009).

Table 3.3 Reference occupancy patterns for a household of four

<i>Schedules</i>	<i>Hours</i>	<i>Occupants</i>	<i>Occupied areas</i>	<i>Description of activities</i>
07:00 – 15:00	8	1	living-area and bedrooms	<i>lightly to moderately active:</i> meal preparation, child-care, cleaning, cooking, ventilating
15:00 – 19:00	4	3	living-area	<i>moderately to lightly active:</i> ironing, laundry, studying, reading, playing computer
19:00 – 23:00	4	4	living-area and bedrooms	<i>lightly active to sedentary:</i> seated watching TV, resting, relaxing, family dining
23:00 – 07:00	8	4	bedrooms	<i>sleeping hours</i>

Note: the reference household profile is set for the purpose of assessing variations in building design, occupancy pattern are subjected to large variations from household to household

Energy consumption for household users in **Table 3.4** are derived from regional consumer data from the latest national survey by the ministry of energy (MINEN, 2010), and simulations performed for the base-case. Average consumption data for other energy end-uses other than space-heating given per household from the results of the survey are converted into useful energy using appliance efficiency factors listed in Appendix 8.4 —differences in energy use in the same region between one household and another can reach up to over five times mostly due to income effects (MINEN, 2010). As reference for the purpose of comparisons through simulations, space-heating energy is estimated assuming use of individual room heaters in the living area and all bedrooms of the base-case, considering a single heating period of 16-hours (7am -11pm), and a lower thermostat setting of 17°C from the months of May to September (see the effects of varying space heating assumptions and initial dwelling conditions on energy use in Sections 2.3 and 4.5.3).

Table 3.4 Reference domestic energy use for household users (kWh/year)

Location	Electric equipment	Water heating	Cooking	Subtotal (residual uses)	Space-heating	Total
Antofagasta	1,600	1,600	800	4,000	500	4,500
Santiago	1,800	1,800	900	4,500	1,800	6,300
Puerto Montt	2,000	2,000	1,000	5,000	3,900	8,900

Note: based on average data for residual energy uses by MINEN (2010), with maximum national reported values exceeding 10,000 kWh/year per household; space-heating energy is based on results of simulations performed for each location listed in the table (see Figure 2.1).

A reference internal heat load from occupants and appliances are given in **Table 3.5**. Occupancy heat gains are subjected to high uncertainty and variability over time and from one household to another. This study does not attempt to reproduce occupant behaviours, but to compare under uniform criteria the effects of variations in building design. An averaged whole-house heat load of 10 W/m² is assumed as an acceptable reference value based on current appliance usage (CNE, 2014), and assumptions from previous research (Müller 2006; Bustamate, 2009; Hatt et al., 2012). Translated to hourly values, this is for any given area in the base-case a value of 5.0 W/m² per occupant, 5.0 W/m² for electric equipment and lighting, and 10 W/m² for appliances in the living and kitchen area. Considering the occupancy schedule of the reference household, hourly heat load values for simulations are:

Table 3.5 Reference hourly heat gains from occupants and appliances

Area	Source	Room Internal (sensible) Heat gains W/m ²																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Living area	occupants	-	-	-	-	-	-	5	5	5	5	5	5	5	5	15	15	15	15	15	20	20	20	-	-
	appliances	-	-	-	-	-	-	5	5	5	5	5	5	5	5	5	5	5	5	5	10	10	10	-	-
Bedroom 1 (main bedroom)	occupants	10	10	10	10	10	10	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	10	10
	appliances	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	5	5
Bedroom 2	occupants	5	5	5	5	5	5	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	5	5
	appliances	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	5	5
Bedroom 3	occupants	5	5	5	5	5	5	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	5	5
	appliances	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	5	5
Kitchen area	appliances	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Bathroom	appliances	-	-	-	-	-	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	5	5
Total number of occupants		4	4	4	4	4	4	1	1	1	1	1	1	1	1	3	3	3	3	3	4	4	4	4	4

Note: indicative values used for computational simulations estimated for the base-case dwelling of 70 m² (only sensible heat gains are considered)

3.4.1 Indoor Thermal Comfort

In naturally conditioned dwellings indoor comfort temperatures are influenced by changes in outdoor climate conditions. Extensive revisions of field studies on occupant thermal comfort by Humphreys (1978, 2010, 2013) and de Dear (1997, 2001, 2011), demonstrate that the most important environmental parameter to predict indoor comfort temperatures in buildings that are free running is the range of outdoor temperatures —other variables are indoor space temperatures, relative humidity and air-speed (Peeters & de Dear 2009). Similarly, the results of the survey carried out for this project show that the preferred indoor temperature reported by dwelling users was correlated to the prevailing outdoor temperature. To extend the analysis on occupant thermal comfort requirements, the following expression derived from a large database of field studies on residential buildings by de Dear & Bragger (1997, 2001) is used:

$$\begin{aligned} T_{\text{comf}} &= 17.8 + 0.31 \cdot T_o \\ T_{\text{lim}} &= T_{\text{comf}} \pm 3.5^\circ\text{C for 80\% acceptability} \end{aligned} \quad (3.3)$$

where T_{comf} is the comfort temperature for a given day and T_o the outdoor temperature of the same day taken as a weighted running mean (de Dear 2011, Humphreys, 2013).¹ The results of the survey of this study show that the range of preferred temperatures reported by users of dwellings is 7K considering 80% of the respondents being satisfied and thus assumed as an acceptable range. As an indication, daily mean whole-house temperatures of 19–23°C are target comfort values obtained for typical cold and warm season days with upper and lower comfort limits of 17–24°C and 20–27°C respectively. Provided that acceptable comfort temperature ranges are achieved, further design improvements are needed to increase the choices available for occupants to suit individual requirements over time.

The strategy to achieve occupant thermal comfort in standard dwellings focuses on improving specification of envelope constructions and glazing as well as design of operable elements. Based on simulations for the base-case, following specification of envelope structural materials, internal finishes and external insulation adjustments of room glazing size are required for additional solar heat gains to raise indoor daytime temperatures by 7K during cold days. However, if no further measures are taken, additional heat losses and gains from glazing may also be a cause of occupant thermal discomfort during other periods of the year. To prevent this during periods of highest heat losses, practicable insulated shutters on glazing are provided to allow occupants increase indoor room temperatures by 2.5K in evenings, overnight, and early mornings (see results of parametric variations in Section 4.4.1).

3.4.2 Airtightness and Ventilation

Operable means to control air exchange rates are provided for dissipation of excess heat gains, minimisation of heat losses and maintenance of indoor air quality. The sizing of operable window components is the main strategy considered to prevent occupant thermal discomfort over the cooling season as their adequate use can help lowering daily mean indoor temperatures in the order of 3K or higher (see results of simulations in Figure 4.7, Section 4.4.4).

When required by location using ceiling fans during hot daytime hours at peak season days may also be considered. For the heating season, the objective is to minimise heat losses from air infiltration and ventilation while ensuring adequate outside fresh-air intakes can be provided to occupants either through natural means or mechanically making use of heat recovery systems.

Based on recent empirical evidence by Figueroa et al. (2013), a whole-house air exchange rate of 1.0 ac/h is assumed as constant air infiltration rate for simulations with the base-case. Results of blower door testing performed for 200 dwellings by Figueroa et al., to propose a national baseline showed minimum whole-house airtightness values of 0.45 ac/h the equivalent of 9.0 m³/hm² at 50 Pa; with a sample average of 1.2 ac/h (24.6 m³/hm² at 50 Pa); and maximum values ranging above 5.0 ac/h (40 m³/hm² at 50 Pa). For simulations with the base-case dwelling in this study a constant value of 1.0 ac/h is assumed considering further improvements if required by location (see effects of varying air-exchange rates in Figures 8.6, 8.9 and 8.11, Appendix 8.5).

An additional room air exchange rate of 30 m³/h per person is assumed to comply with indoor air-quality guidelines by MINVU (2015). Considering the occupancy profile of the reference household of four additional ventilation rates to comply with indoor air quality requirements translate into 0.5–1.0 ac/h per person, depending on room size. Controllable means for minimising ventilation over periods of low outdoor temperatures are provided for occupants to improve temperatures by allowing minimum additional room air exchange rates of 20 m³/h per person. This is achieved in dwellings by installing window-frame vents which will contribute to adjust indoor room temperatures by 2K when required by the occupants (see specifications for trickle vents in Figure 4.1 and results of simulations in Figure 4.15).

3.4.3 Daylighting

Exterior shading devices are provided for control of unwanted solar heat gains and sized to allow adequate access to daylight. An average room daylight factor of 5% is considered an acceptable level for natural illumination in residential premises (MINVU, 2016). In standard dwelling designs higher values should be achieved through adjustments of glazing areas to balance visual and thermal comfort and displace conventional energy uses. To prevent daytime overheating from additional glazing areas the use of external adjustable louvers allows occupants to lower indoor temperatures by 2.5K during peak warm periods (see simulation results in Section 4.4.3).

3.5 Conclusion

New dwelling stock is being built to poor regulatory thermal and energy efficiency standards. The most concerning gap identified through the review of the current regulatory system (CTR, 2007; OGUC, 2015) and standards (NCh-1079, NCh-851, NCh-853) in this chapter is the lack of evidence-based criteria for addressing occupant thermal comfort. The evidence reviewed indicates that the current approach to predicting energy consumption in dwellings is favouring development of costly inefficient and fuel-consuming space condi-

tioning technology. The following list reviews the most relevant gaps identified for improving the thermal efficient design of dwellings economically:

- there is need for distinct design specifications for all *dwelling types* including least exposed apartments
- criteria are required to ensure adequate *thermal capacity* is provided in the building structure and finishes particularly for inland locations
- statutory *thermal insulation* levels need revision for optimizing heat-losses as a function of dwelling type as well as increasing insulation for exposed walls considerably and ground floor on cold locations
- regulation of *air-infiltration* and *minimum ventilation* standards are needed to achieve acceptable indoor thermal comfort without detriment to air quality in homes
- design criteria are required to balance the ratio of *glazing to opaque envelope* for control of unwanted and useful solar heat gains
- specifications of *operable envelope elements* on glazing (insulation and solar control) are desirable for improving occupant comfort at low cost
- careful design considerations are required to prevent summer discomfort and overheating particularly in intermediate-floor apartments
- criteria for integration of energy-efficient and non-polluting appliances are recommendable to improve dwelling thermal efficiency (i.e. low-radiant electric heaters and/or cooling fans)

¹ The weighted running-mean of the daily mean outdoor dry-bulb air temperature is calculated from the series: $T_{rm} = (1 - \alpha) \{T_{od-1} + \alpha \cdot n-1T_{rm}\}$; where T_{rm} is the running mean temperature for day n and $n-1T_{rm}$ the running mean temperature for the previous day.

4 Design of Naturally Conditioned Dwellings

4.1 Introduction

The techniques applied in this chapter are designed to minimise the energy and capital costs required to achieve occupant thermal comfort conditions in new standard dwellings. Extensive analytical work was carried out to assess the influence of different design measures on seasonal, daily and hourly distribution of room temperatures. Results of dynamic thermal simulations indicate that comfortable indoor temperatures can be achieved across a wide range of locations at low extra capital costs and without recourse to conventional energy for space-heating and cooling. Design guidelines are translated into parametric models containing specifications for passive acclimatisation of dwellings in multi-unit residential developments.

4.2 Design Guidelines

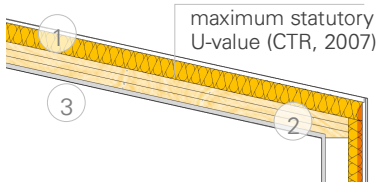
The effect of different design measures on thermal comfort is assessed for different seasons and time scales over a year using a dynamic thermal computational simulation tool: thermal analysis software TAS, version 9.4 (EDSL, 2016). Comfort temperature ranges are estimated on a day-to-day basis using hourly outdoor dry-bulb temperature data obtained by location from Meteoronorm data base, version 7.2 (Meteotest, 2016). Thermal simulation analysis performed on multi-zone building models focuses on operative temperatures, an average between the dry-bulb air and mean radiant temperature of individual rooms. Based on field studies and simulations performed for this study, guidelines to achieve occupant thermal comfort in standard dwellings specified to meet minimum statutory regulations are proposed, namely to:

- ensure adequate thermal capacity is available in the building structure and interior envelope surfaces of habitable rooms
- provide additional levels of thermal insulation for exposed opaque walls and when required for exposed ground floor elements
- adjust the size of windows as a function of orientation, room size, and occupant requirements for passive solar heat gains
- provide internal insulated shutters on exposed glazing elements for control of excess heat losses during evenings and overnights
- provide controllable means for ventilation such as adjustable trickle vents, extract fans and/or individual heat recovery ventilators
- provide operable shading devices on north, east and west facing windows with adjustable blinds for control of excess solar heat gains and

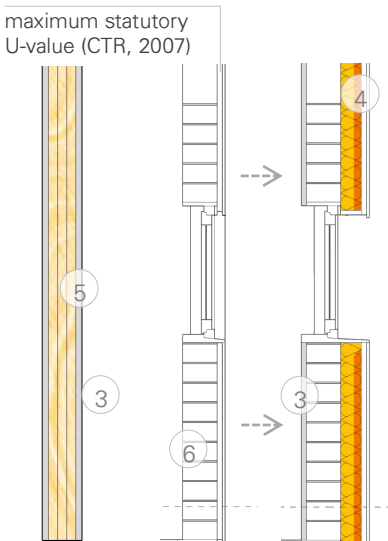
Figure 4.1 Specification of building envelope and interior finishes

Indicative building specification details for increasing the heat storage capacity and envelope insulation of standard base-case dwellings.

roof and ceiling elements



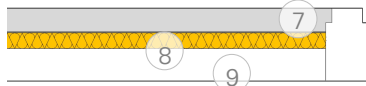
partitions and vertical structure



intermediate slab (if apartment)



ground floor



material properties

(specifications for Santiago)

1. roof insulation (80mm)
2. CLT panel (90mm)
3. cement plaster (20mm)
4. wall insulation (100mm)
5. solid clay brick (140mm)
6. high density concrete (100mm)
7. floor insulation (cold locations)
8. compressed gravel (500mm)

Figure 4.2 Placement of thermal mass and envelope insulation

Thermal capacity is added to structural building elements and on internal surfaces in habitable rooms and thermal insulation is placed on exterior envelope elements ensuring continuity and integrity

- internal luminous levels
- make provisions for heat dissipation and night cooling through adequate sizing and placement of window openings (consider using ceiling fans or ventilators during peak-hot daytime hours)

The proposed design techniques and specifications are illustrated from Figure 4.1 to Figure 4.4 accompanying the section. The effect of each design parameter on daily patterns of operative temperatures are explained as expected from results of simulations for cold and warm season days in Figure 4.6 in the following section. The contribution of each design parameter to achieve occupant thermal comfort depends on the initial conditions of the dwelling as well as the cumulative effect of variations and controls operated by the occupants (see summary of parametric variations in Figure 4.5). Specific design objectives and performance criteria for application of each technique are discussed below.

As depicted in **Figure 4.1** and **Figure 4.2**, the thermal capacity of dwellings is provided in structural building elements, partitions and internal finishes in habitable rooms. This first set of specifications which are crucial for choosing a suitable building construction material contributes to regulate day-to-day temperature fluctuations more than any of the proposed techniques (see performance effect on daily graphs in Figure 4.6). By delaying the daily cooling-down and warming-up periods and reducing respective peaks in room operative temperatures the use of massive structural materials and finishes provides a more stable thermal environment for passive heating and cooling.

Additional layers of thermal insulation are placed on the exterior side of exposed wall and/or floor elements (Figure 4.1) —no higher values than minimum national standards are considered for other elements (CTR, 2007). The design objective is to ensure daytime room operative temperatures reach the

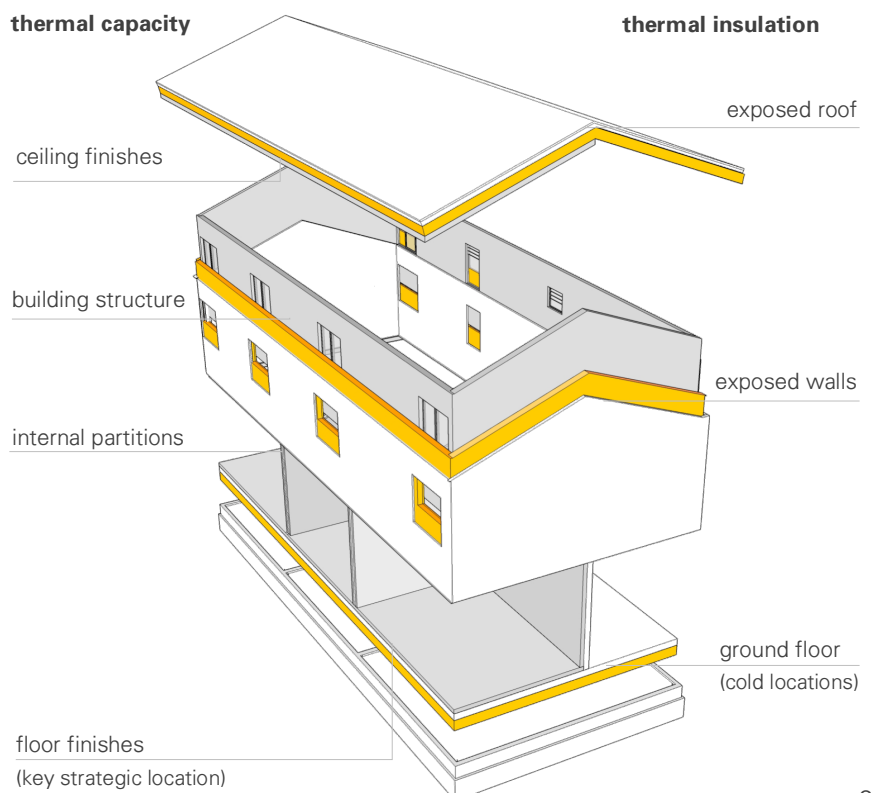
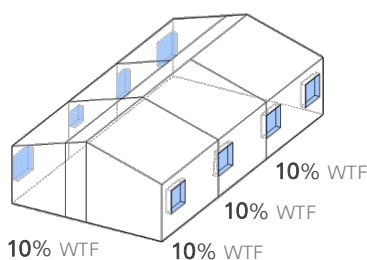
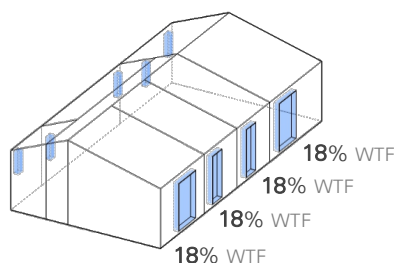


Figure 4.3 Orientation and size of room glazing areas

a. 45-55% distribution of glazing areas between orientation, room window-to-floor areas as follows:



b. 20-80% distribution of glazing areas between orientation, room window-to-floor areas as follows:

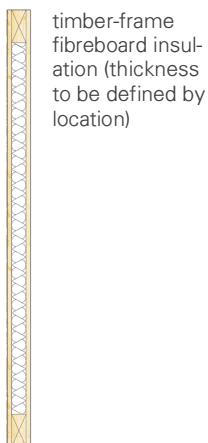


lower comfort limit during cold days (see target effect on Figure 4.6). During warm days the addition of thermal insulation will cause no penalties to occupant thermal comfort in dwellings whereas in least exposed apartments the accumulation of excess heat gains will be more prone to cause overheating. Consideration should be given for minimising the additional capital costs and high embodied energy and carbon emissions of mainstream insulating materials such as polystyrene, fiberglass and polyurethane foams.

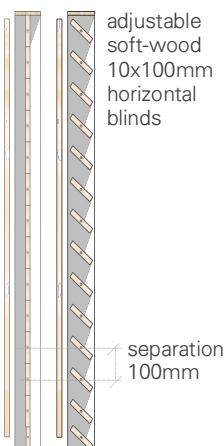
The glazing area of the building envelope is distributed so as to both ensure solar heat gains are available in habitable rooms and also minimising heat losses in less demanding areas. As shown in **Figure 4.3**, this is accomplished by grouping the glazing areas of living areas and bedrooms along the northern façade and increasing their respective size relative to room floor areas.

The effect of additional heat losses and incidental solar gains in rooms with relative larger glazing areas is moderated by the thermal capacity of the interior envelope structure as well as by use of operable shutters and blinds designed to be made and installed economically.

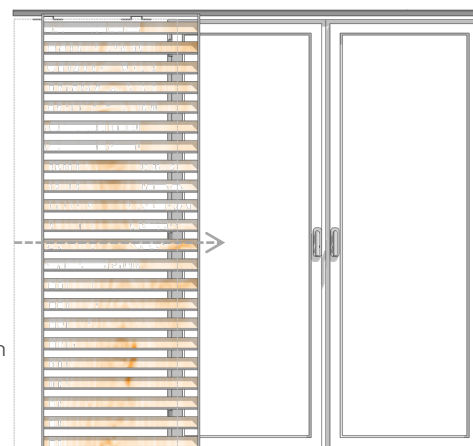
The effect of a number of design techniques will depend on the specification of window elements and operable features (**Figure 4.4**). During periods of low outdoor temperature and sunshine levels lowest peaks in heat losses can be avoided with use of insulated shutters installed on the inside of window openings. Designed for user-friendly operation, excess winter ventilation can be also minimised with operable trickle vents fitted through the

Night insulation**Window vents**

aperture size
 0.071m^2 (living area)
 0.024m^2 (bedrooms)
 max. ventilation rate of 8.0 l/s/p

**Exterior shading****Window openings**

fully operable vinyl windows, minimum aperture size specified by location

**Figure 4.4 Specifications of practicable envelope elements**

Subjected to adjustments by location according to results of simulations for achieving comfort temperature ranges and individual occupant requirements.

side of window frames. When outdoor temperatures rise above comfort limits, overheating due to accumulation of excess solar heat gains can be prevented with use of exterior shading and control of operable blind angles. Further cooling can be provided in rooms through different ventilation strategies designing and placing window apertures and vents accordingly.

4.2.1 Methods and Tools

The simulation software allows comparing the effect of different design techniques under controlled weather and occupancy conditions (see input data for simulations in Appendix 8.5). TAS solves the various heat transfer processes occurring within buildings on time-steps of one hour and over an analysis period of one year (EDSL, 2011). For each step through simulations in and outgoing heat fluxes through conduction, convection and radiation are modelled with user generated data for outdoor weather, internal conditions and building element specification (see Sections 8.5.1, 8.5.2 and 8.5.3). Although the accuracy and reliability of TAS have been validated with empirical measurements taken for residential buildings (EDSL, 2014; Amoako-Attah & B-Jahromi, 2015), there are limitations and uncertainties requiring acknowledgement for careful interpretation of results in this study:

The *weather data* used for simulations is based on long-term standardised meteorological measurements collected and converted into hourly year-reference formats by Meteonorm software (Meteotest, 2016). These weather datasets were developed for building simulations including averaged annual hourly data taken from existing meteorological stations over specific measurement periods, namely for: dry-bulb temperature, solar global radiation, solar diffuse radiation, wind-speed, wind direction, cloud cover and relative humidity (see weather files for all locations in Table 8.12, Section 8.5.1). Due to this data collection procedure a limitation of this study is that simulations do not take into account the effect of specific building site conditions nor extreme or future weather (see design options and alternatives in Table 4.2). The locations selected for parametric simulation analysis are:

- **Santiago** (33°50'S 70°67'W): met-station *Pudahuel*
- **Antofagasta** (23°43'S 71°43'W): met-station *Antofagasta*
- **Puerto Montt** (41°41'S 73°08'W): met-station *El Tepu*

Internal condition data was set for different dwelling areas in TAS using the reference occupancy schedule and values defined for a target household of four (see target households and selection criteria in Section 3.2). Detailed hourly input data for internal heat gains from occupancy can be consulted in Table 3.5, whereas hourly infiltration and ventilation input rates are given in Table 8.13 in Appendix 8.5. Since it is not the purpose in this study to represent occupant behaviours the input data used for simulations are reference values set for comparing the effects of building design variations. Other than changing internal condition parameters individually (see results of simulations in Figures 8.6, 8.8 and 8.11), no uncertainty analysis was undertaken due to lack of representative empirical measurements and probability distributions at the time of publication. As a general indication for any given area in dwellings

the following criteria apply:

- *Air-infiltration*: a constant air exchange rate of 1.0 ach ($2.6 \text{ m}^3/\text{hm}^2$ at normal pressure conditions), is assumed for all rooms at any given time (see hourly room air exchange rates in Table 8.13, appendix 8.5)
- *Ventilation*: an additional air exchange rate of 1.0 ac/h (8l/s) per person is assumed in occupied rooms at any given time (see airtightness and ventilation criteria in Section 3.4)
- *Occupancy heat gains*: of 5.0 W/m^2 per person in occupied rooms, 5.0 W/m^2 for lighting and equipment, and 10 W/m^2 for kitchen appliances (see hourly input data in Table 3.5)

Building element data was assembled manually for the simulation software using material properties listed in Chilean standard NCh-853 (Of. 2007), and when available taken directly from the suppliers (Appendix 8.2). Although building material attributes are derived from results of laboratory tests taken from specified sources their actual performance and maintenance over time is another source of uncertainty requiring judgement beyond the intend of this study. The internal zoning and building element distribution of the dwelling models used in TAS 3D modeler can be consulted in Figures 8.2 and 8.3. Detailed specifications for the base-case and improved dwelling models are available in Tables 8.14 and 8.15 respectively in Appendix 8.5.

The modelling method applied through simulations draws on parametric variations performed to base-case models —these are buildings specified with timber frame structure, minimum statutory envelope insulation and glazing size. Two base-case models were used in TAS, one for a single-storey detached and other for an intermediate-floor apartment flat (see input models in Figures 8.2 and 8.3, Appendix 8.5). Each step through simulations illustrated in **Figure 4.5** were specified in TAS to improve the performance of the base-case for each location following the same order given in the figure and in a cumulative manner. The first steps shown in Figure 4.5 and explained in the list below involving changes to fixed building parameters require assessment through simulations over the whole year period whereas operable envelope elements can be assessed over each season individually.

- *Thermal capacity (step 1)*: the timber-frame construction specified for the base-case model in TAS, see respective input data in Table 8.14, is replaced with building materials and internal finishes with higher heat-storage capacity (see specifications in Table 8.15).
- *Thermal insulation (step 2)*: the thickness of external wall insulation is increased, or if not specified, an additional insulation layer is added to the outside of the building element behind the cladding (Table 8.15)
- *Window size (step 3)*: the size of glazing elements is increased in habitable rooms and left to minimum admissible size in service areas by changing window dimensions in TAS 3D modeler.
- *Night insulation (step 5)*: a substitute building element is assigned to windows from dusk to dawn hours using the same glazing properties

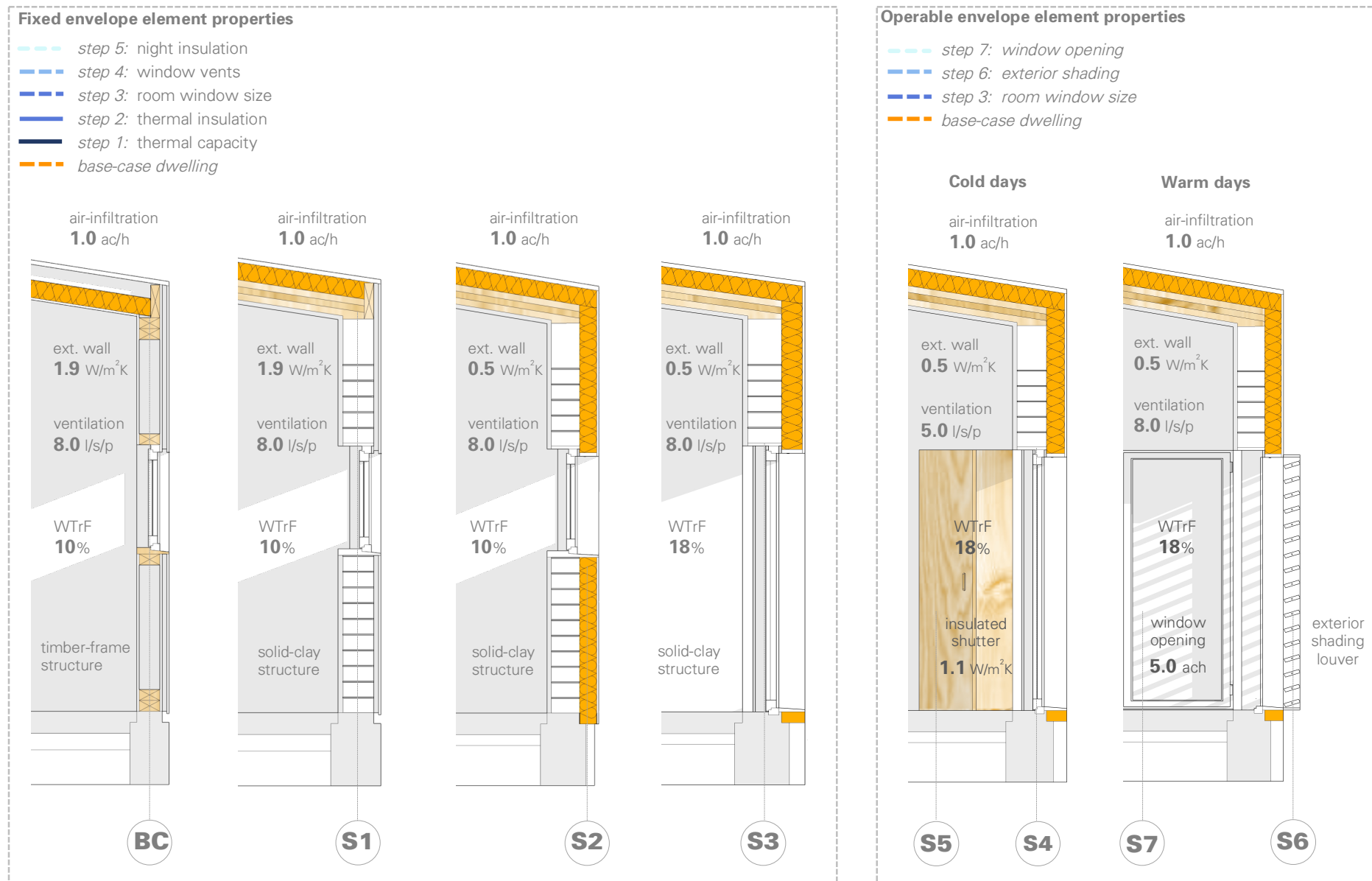


Figure 4.5 Summary of building parametric design variations (improvement measures based on simulations for Santiago)

The steps illustrated in the figure show variations to improve the performance of base case dwellings: specified with timber-frame structure, 10% glazing to floor area and minimum statutory insulation by location (all other building design characteristics as well as air-infiltration and internal heat gains from occupancy are constant). Refer to Figure 4.6 to see the effect of each variation on indoor temperatures, a detailed description and specifications for each design variation are given in the text.

of the base-case and an insulated blind on the inside leaving an air cavity in between (Table 8.15)

- *Window vents (step 6)*: room air exchange rates are decreased to minimum ventilation rates by assuming 0.5 ac/h (5.0 l/s) per person in occupied rooms at any given time (see hourly inputs in Table 8.13).
- *Exterior shading (step 7)*: a feature shade is applied to glazing elements during daytime hours specifying horizontal slats of 100mm spacing and element width according to window size (Table 8.14).
- *Window openings (step 8)*: an aperture type is assigned to window elements using an opening schedule and proportion defined in accordance to occupancy and comfort temperature requirements (Table 8.14).

Figure 4.6 Effect of applying passive design techniques on cold and warm days

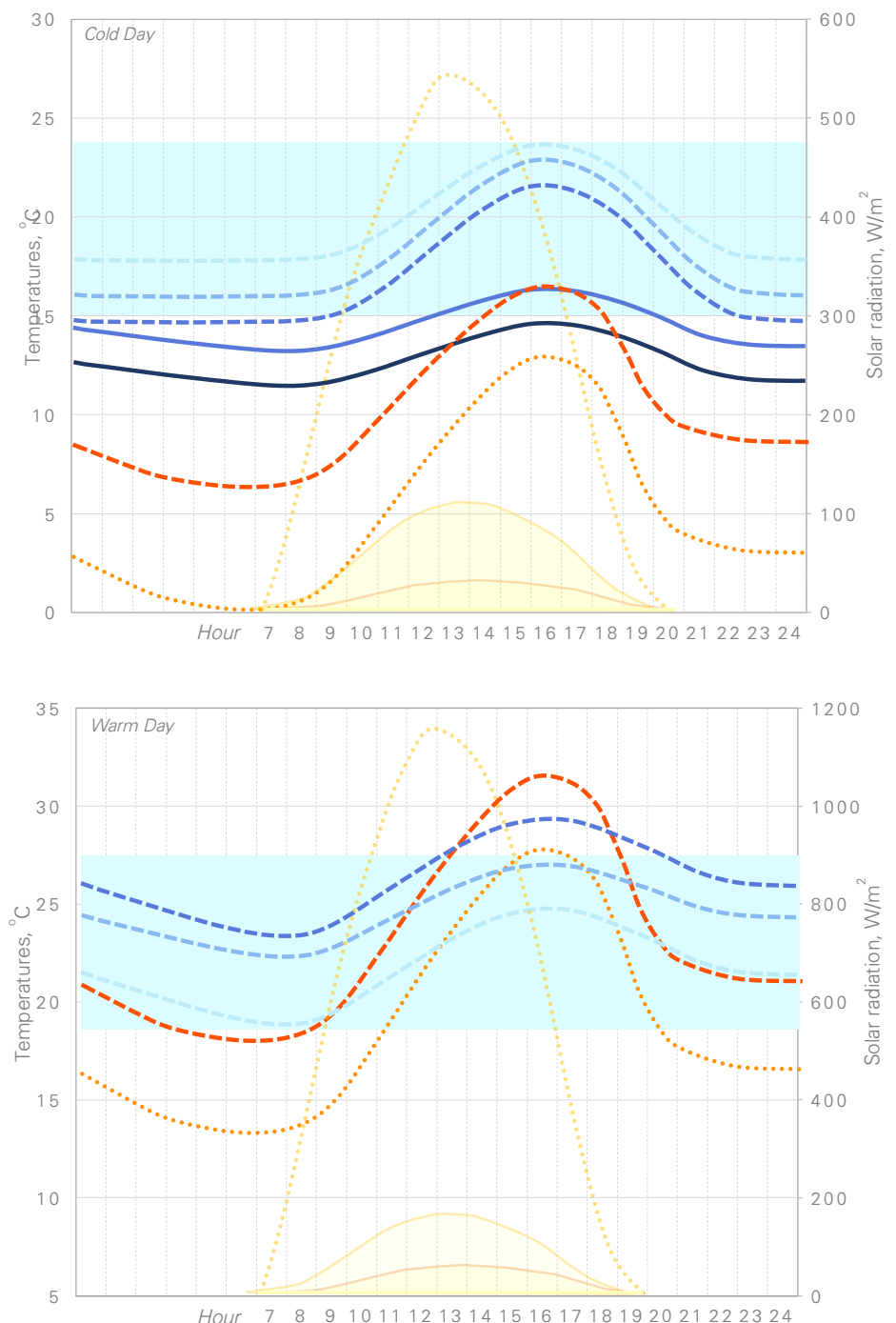
The base-case shown in the figure is a standard base-case dwelling specified with timber frame constructions, 10% window-to-floor area and minimum insulation by location (CTR, 2007). All else: design characteristics, infiltration and internal heat gains from occupancy are constant (see inputs for simulations in Appendix 8.5)

Cold days

- step 5: night insulation
- step 4: window vents
- step 3: room window size
- step 2: thermal insulation
- step 1: thermal capacity
- base-case dwelling

Warm days

- step 7: window opening
- step 6: exterior shading
- step 3: room window size
- base-case dwelling
- outdoor temperature
- outdoor solar radiation
- solar gain (base-case dwelling)
- solar gain (improved dwelling)
- daily comfort range (after de Dear 2010)



The graphs in **Figure 4.6** show the results of simulations from applying design variations over cold and warm season days. The outcome parameters were selected in TAS for assessing operative temperatures or when relevant other variables influencing performance such as incidental solar heat gains or air-exchange rates (Figures 4.19 to 4.28), assessment of other environmental variables influencing comfort was beyond the scope of this study. As shown in the graphs, the orange and yellow dotted lines are the outdoor dry-bulb temperature and global solar radiation for each day in study. The orange broken line and shaded yellow areas the resultant temperature and internal solar heat gain of the base-case and each blue line the improved room temperature range resulting from applying each variation through the simulations.

By paying attention to any possible unwanted effect over the year, the focus of design through simulations is on improving operative temperatures during the cold and warm season days. As shown in the diagrams in Figure 4.6, when required by location, diurnal temperature fluctuations are first narrowed down to about 5K by increasing the heat storage capacity of the building structure (*step 1*). Statutory envelope thermal insulation (*step 2*), and minimum glazing size (*step 3*), are then adjusted to ensure the level of passive heat gains required to reach comfort during cold days. If further required, operable envelope elements are provided for additional individual adjustments using insulated blinds (*step 4*) and/or trickle vents (*step 5*) over cold days, and exterior shading (*step 6*) and/or window openings (*step 7*), over warm days.

4.2.2 Performance of Standard Dwellings

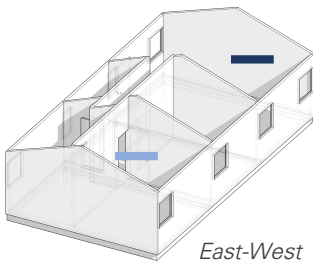
An hour-by-hour analysis of occupant thermal comfort was performed to identify any additional requirement to improve passive design of dwellings in Central Chile. The analysis was carried out for the climate in Santiago (33°S) which among the locations of study has the largest fluctuation in diurnal outdoor temperature with monthly averages ranging above 10K (INN, 2008). During typical cold and warm days, peaks in outdoor temperature range between 0–15°C and 15–30°C with global solar radiation ranging 0.4–1.1 kWh/m² (see daily monthly average distribution in Appendix 8.5, Figure 8.4.1). Although neither the heating nor cooling seasons are severe compared to other regions the adoption of minimum statutory regulations can have adverse effects on occupant thermal comfort and energy consumption, causing significant losses in household disposable income and also high indoor polluting emissions.

Simulations were performed for the standard base-case detached and multi-apartment building, see detailed plans and specifications in Chapter 3, Figure 3.6. The results for the single-storey detached dwelling are plotted for the living area and main bedroom in **Figure 4.7**. As shown in the graph above, during the cold day room temperatures reached the comfort zone only on few daytime hours falling below 15°C in the evening, overnight and early morning. During the warm day room temperatures exceeded the upper comfort limit in the afternoon with values rising above 30°C. In this case, the severity of side-effects from occupant thermal discomfort will be greater over the winter compared to the summer by also bearing an effect on fuel consumption, income capital and indoor combustion emissions.

The results for the standard base-case intermediate-floor apartment are plotted in **Figure 4.8**. For the same dwelling layout and construction, substantial differences were observed on daily temperature patterns. Although the lower envelope heat losses in the apartment contributed to higher winter temperatures overnight, for most daytime hours temperatures drifted below comfort. Inversely, during summer the limited capacity of the apartment to dissipate excess heat caused overheating for most of the day. As the built stock of apartment buildings continues to increase in tandem with the rise in prevailing outdoor temperatures (ECLAC, 2014), the occurrence and intensity of overheating is likely to become a dominant problem.

Figure 4.7 Performance of the base-case detached dwelling

Timber-frame dwelling specified with minimum insulation and glazing size for Santiago. Other than windows (kept closed), no other operable element is in use.



WTF	: 10%
HLC	: 5.1 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

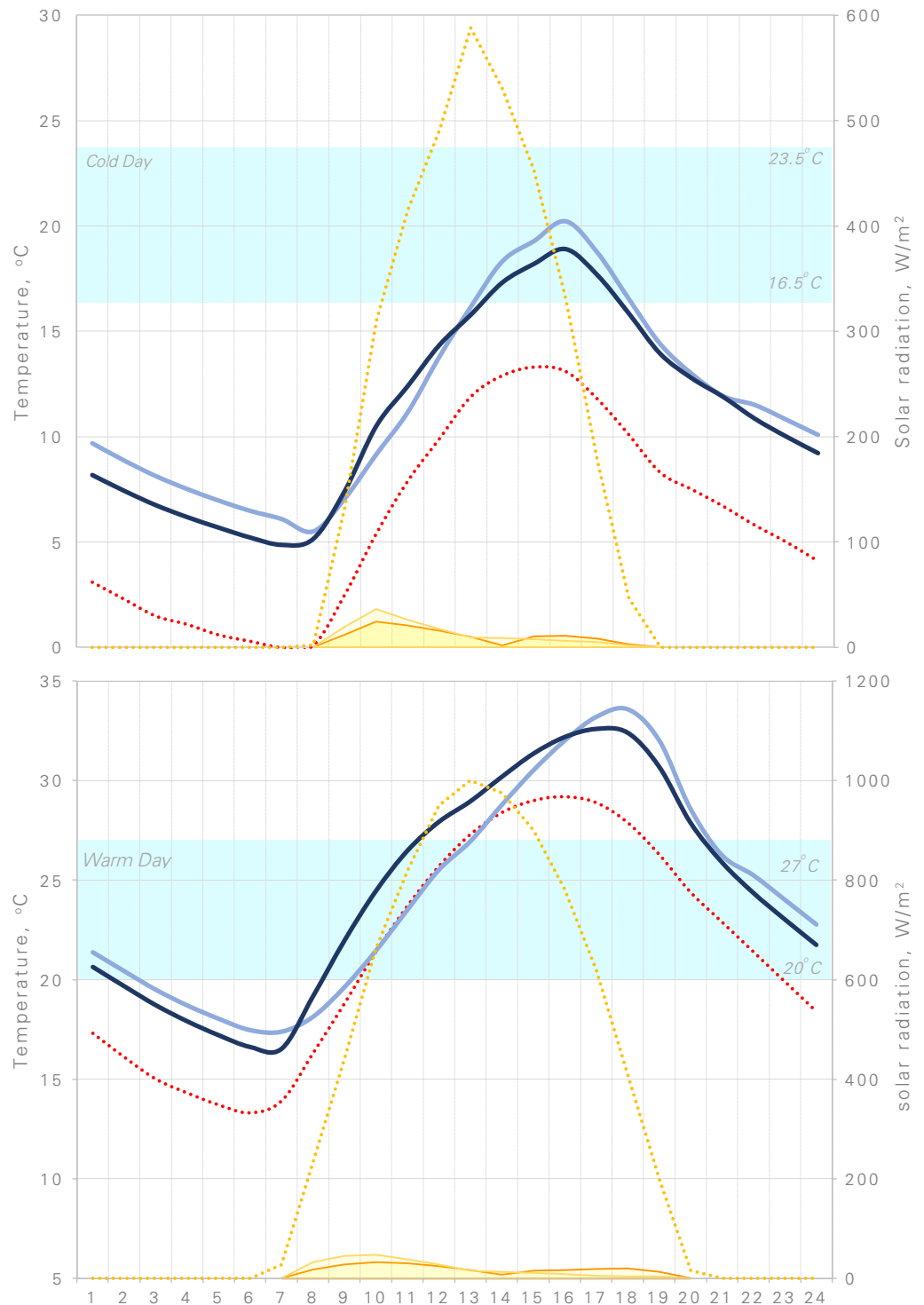
Thermal transmittance, W/m²K

roof	: 0.4
external walls	: 1.9
windows	: 5.8
ground floor	: 1.1

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

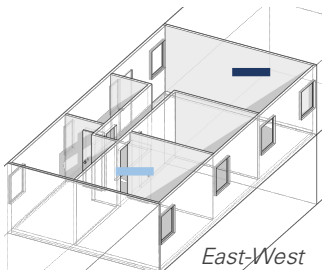
- living area
- main bedroom
- ... outdoor temperature
- daily comfort range (after de Dear 2010)
- ... global solar radiation
- solar gain living area
- solar gain bedroom



Compared to detached dwellings an apartment flat offers advantages in lower space heating energy, running costs and carbon emissions. From the base-case detached to apartment dwellings space-heating energy use decreases by 10 kWh/m² per year. This translates into monthly savings of 5-15% for the poorest and middle income quintiles (CASEN, 2013), with half the pollutant emissions produced by a conventional kerosene heater, an annual load of 14mg/m² of PM_{2.5}, CO, NO₂ and SO₂ (see emission factors in Appendix 8.4). It can be concluded so far from the results of the analysis that to improve the thermal performance of dwellings in central regions the emphasis should be placed on maximising the combined effects of passive solar heating and ventilation with the highest envelope heat-storage capacity.

Figure 4.8 Performance of the base-case apartment flat

Multi-storey timber-frame building specified with minimum insulation and glazing size for Santiago. Other than windows (kept closed), no other envelope element is in use.



WTF	: 10%
HLC	: 3.9 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

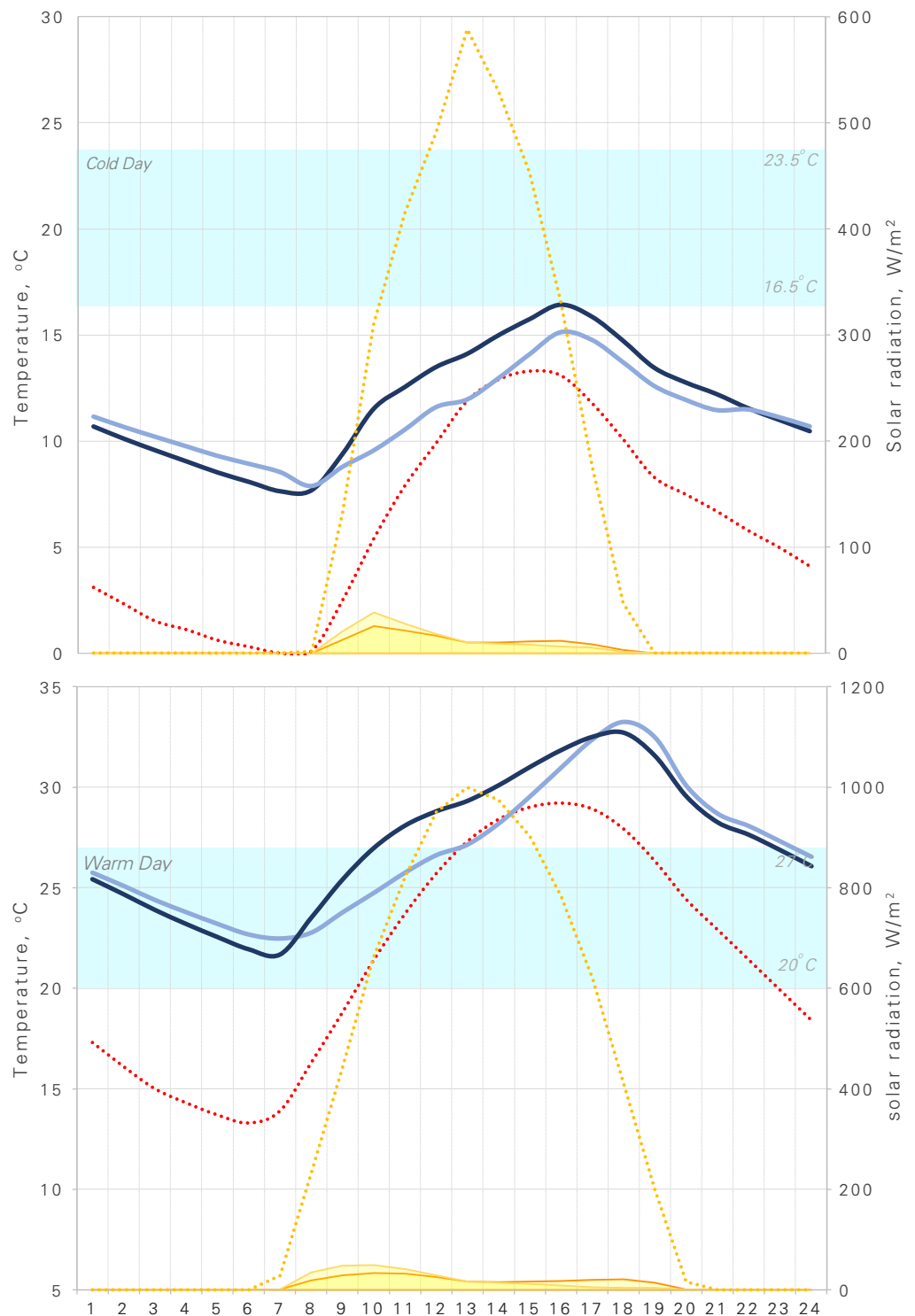
Thermal transmittance, W/m²K

external walls	: 1.9
windows	: 5.8

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

- living area
- main bedroom
- ... outdoor temperature
- daily comfort range (after de Dear 2010)
- ... global solar radiation
- solar gain living area
- solar gain bedroom



4.3 Specification of the Building Envelope

Parametric design variations were carried out for the climate of Central Chile in a location for Santiago to assess possible improvements in dwelling thermal performance. The implications of different design decisions on occupant thermal comfort and consumption of fuels for space-heating are discussed into more detail in this section. The planned capital costs allocated for the construction of the building envelope are weighed against the conventional fuel displaced by optimisation of building design parameters. The results indicate that a high standard of thermal comfort can be achieved and large capital savings can be provided to occupants of all income levels.

Table 4.1 presents a summary of the design variations applied to the base-case detached dwelling for Santiago. This is the standard single-storey detached house which has a space-heating energy load of 25 kWh/m² per year and whose specifications are: lightweight timber-frame structure, minimum insulation standards for exposed roof and walls (CTR, 2007) and 10% window-to-floor ratio (HSFP, 2012), no building controls other than openable windows (see specifications in Figure 3.6 on the preceding chapter). The results of parametric simulations are presented for winter and summer weeks at the end of each section. A thorough discussion of the results follows.

4.3.1 Thermal Capacity

From the weekly graph in **Figure 4.9**, it is clear that the thermal capacity of dwellings has an influential and long-lasting effect on occupant thermal comfort. As specified on Table 4.1 the use of heavyweight masonry walls and partitions instead of traditional timber-frame constructions reduce the difference between the lowest and highest temperature peaks and daily comfort limits by as much as 5–7K on each season and all throughout the year (see changes in construction input data in Appendix 8.5). During cold and warm days, the respective daily lowest and highest temperature peaks obtained by

Table 4.1 Summary of parametric specifications for Santiago

<i>Building parameter</i>	<i>Description</i>	<i>Base case</i>	<i>Improvement</i>
Thermal capacity	timber-frame construction replaced by masonry construction using brick and light concrete blocks with plaster	1.6 Wh/m ³ K	60 Wh/m ³ K
Thermal insulation	the thickness of external wall insulation was increased from 10 to 100mm	1.9 W/m ² K	0.5 W/m ² K
Window size	the window-to-floor (WTF) ratio of the dwelling was doubled (only glazing areas are considered)	10 % WTF	20 % WTF
Orientation	the distribution of windows was arranged to orient most glazing areas toward the equator	East-West	North-South
Night insulation	internal shutters assumed closed from 20:00-8:00 hrs. (the U-values besides consider glazing plus shutter)	5.8 W/m ² K	1.0 W/m ² K
Operable vents	room air-exchange rate reduced by half assuming window vent openings kept at minimum (5.0l/p/s)	1.0 ac/h	0.5 ac/h
Exterior shading	window blinds positioned horizontally, shading factor (SF)	1.0 SF	0.4 SF
Window openings	windows assumed opened by 10% of room floor area overnight from 20:00-8:00 hrs.	1.0 ac/h	10 ac/h

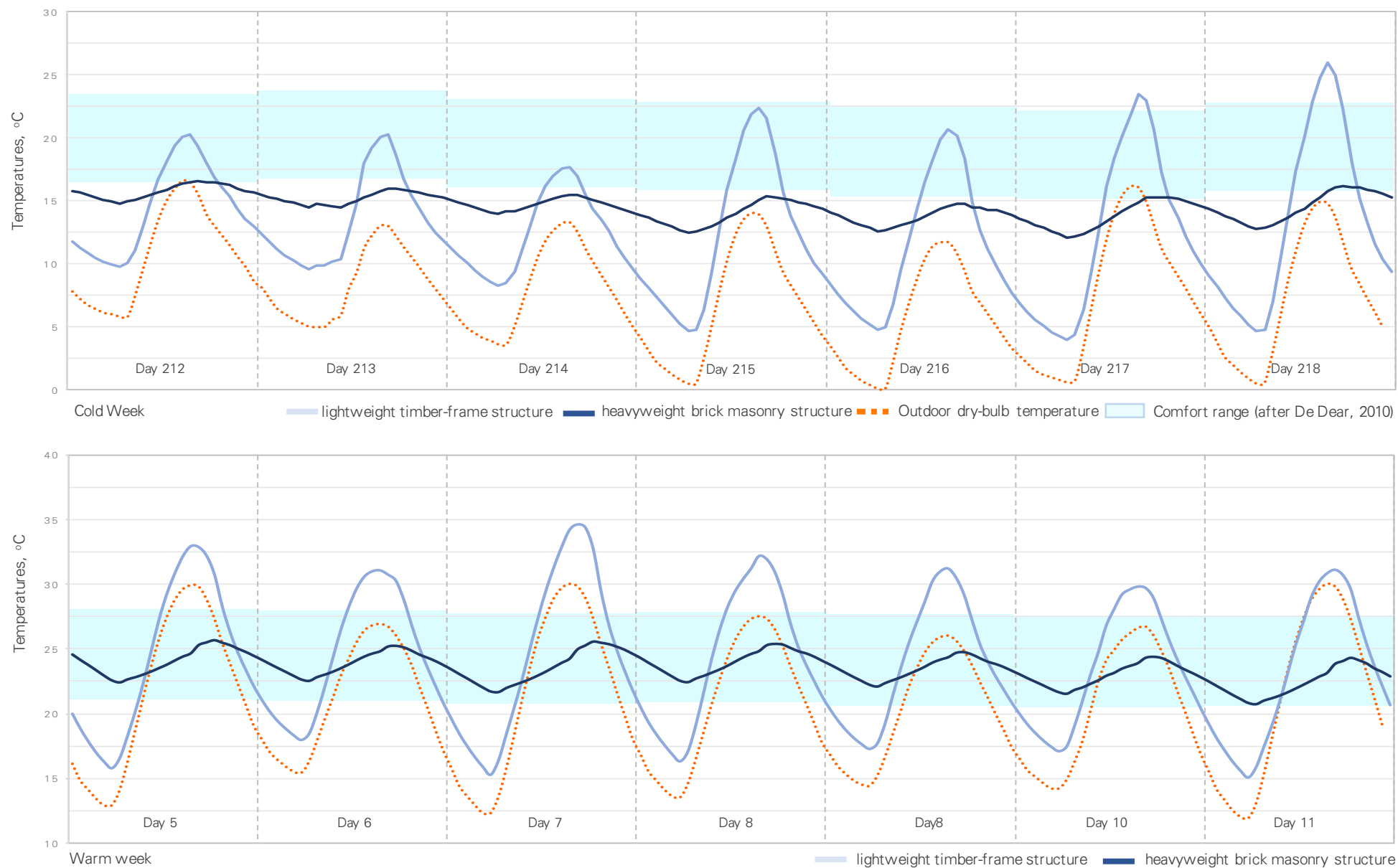


Figure 4.9 Effect of increasing building thermal capacity (detached single-storey dwelling)

Typical timber-frame envelope structure is compared to a heavyweight masonry structure (traditional solid clay brick and light-concrete blocks with plaster finishes, see construction specifications in Figures 4.1 and 4.2). Both envelope structures consider minimum statutory insulation for exposed walls ($U=1.9 \text{ W/m}^2\text{k}$) and roof elements ($U=0.4 \text{ W/m}^2\text{k}$).

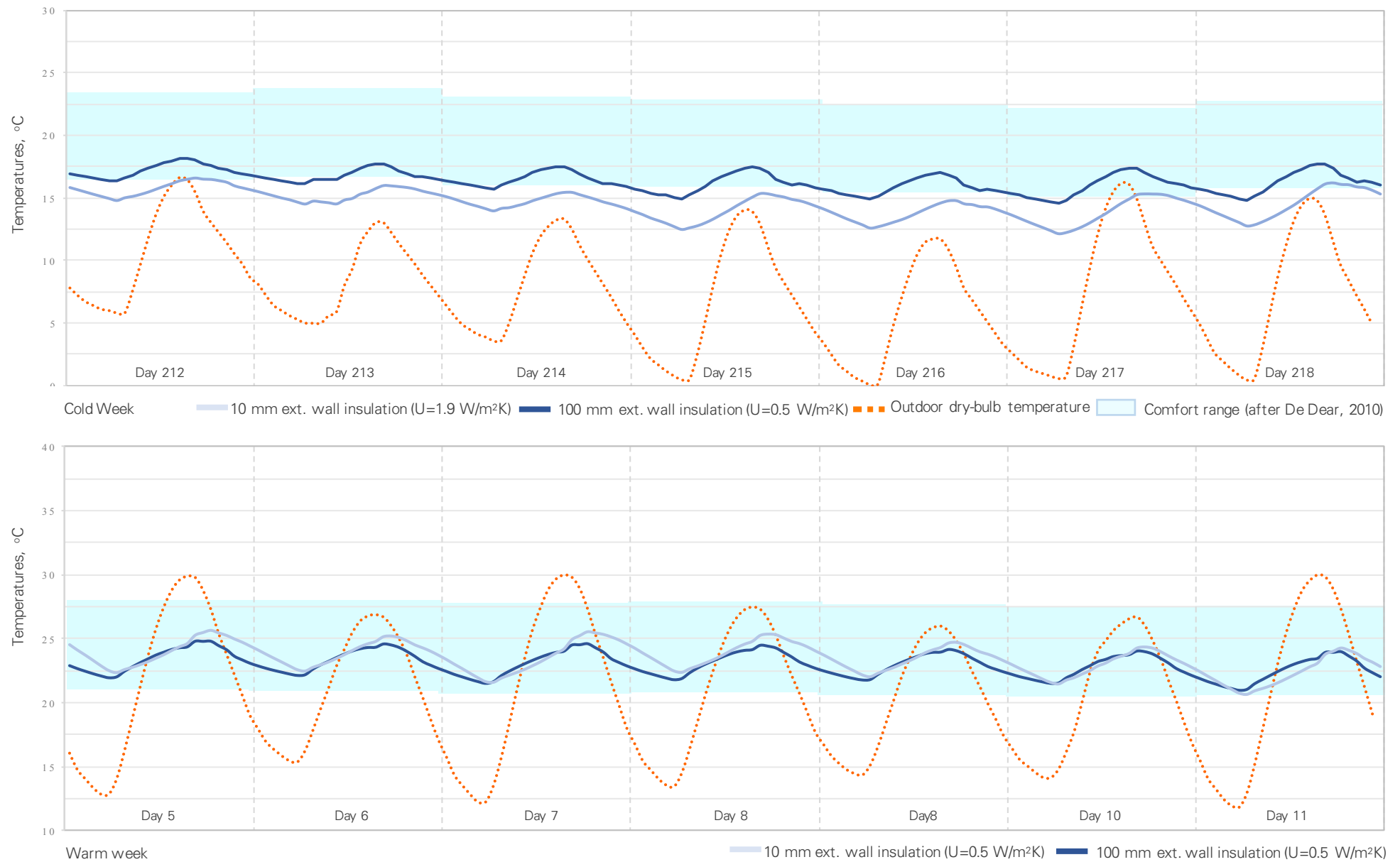


Figure 4.10 Effect of increasing wall thermal insulation (single-storey detached dwelling)

The thermal transmittance (U -value) of exposed wall elements is decreased from $1.9 \text{ W/m}^2\text{K}$ (CLT, 2007) to $0.5 \text{ W/m}^2\text{K}$ by increasing the thickness of external insulation (expanded polystyrene board) specified from 10 to 100 mm (based on results of simulations for the living area)

applying the masonry construction resulted in 13°C and 25°C. The improved heavyweight masonry structure reduced the annual space-heating energy of the timber-frame house from 25 kWh/m² to 15 kWh/m² saving nearly half of the total energy use estimated for the base case dwelling.

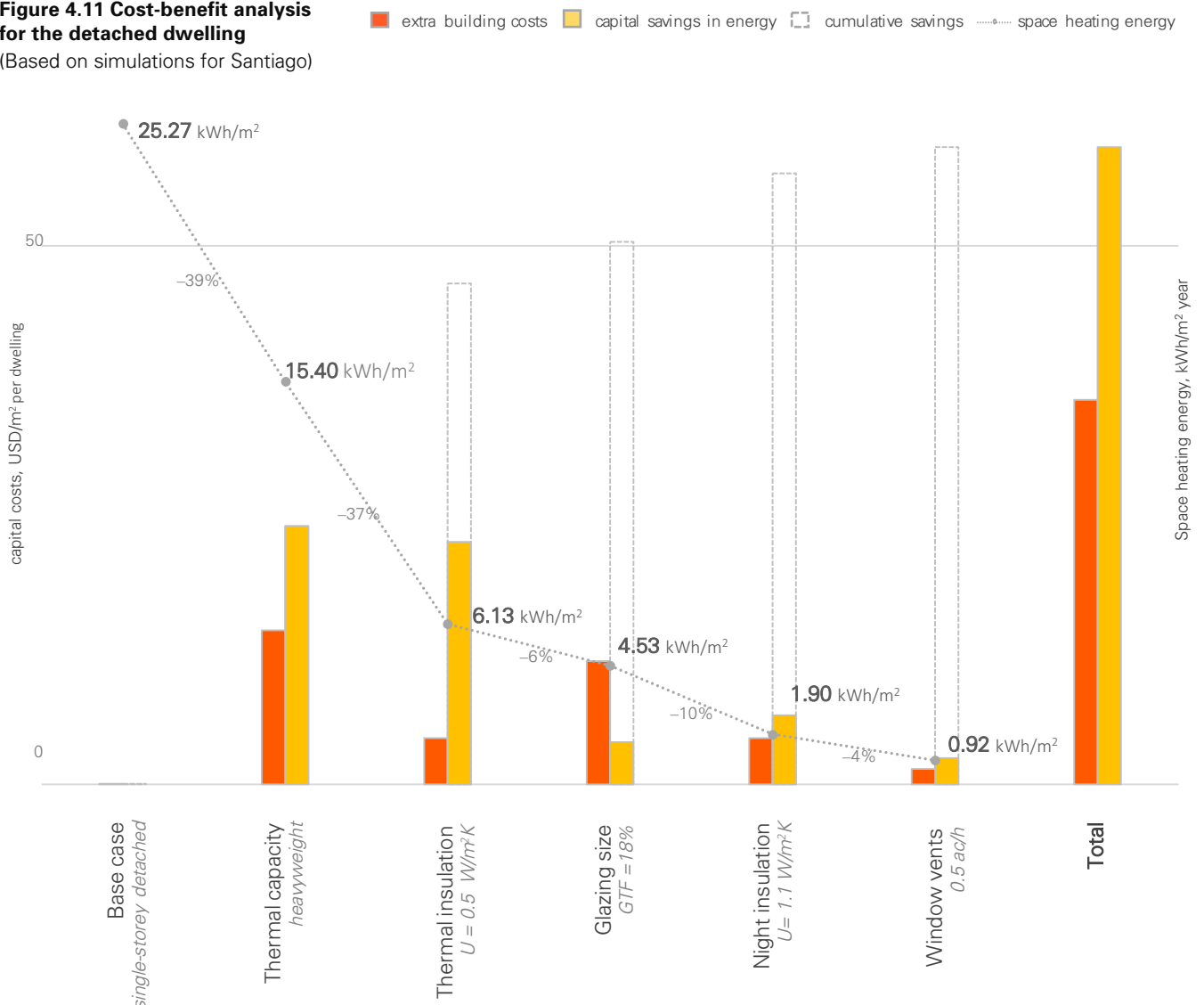
As well as improving occupant thermal comfort, the capital cost estimated for increasing the heat-storage capacity of the building structure was low compared to savings achieved in space heating energy. When applied to a standard masonry dwelling the extra capital investment required to increase the available thermal capacity was 14 USD/m², the equivalent of 2.9% of the minimum housing cost allocated by the government (**Figure 4.11**). Based on a projection of ten years of use, the cost benefit ratio of the investment in construction resulted in 1.87 which means that over the same period occupants would have spent 180 USD less in space heating costs per annum.

4.3.2 Thermal Insulation

Combined with the masonry structure, the addition of thermal insulation contributed significantly to improve thermal comfort in winter, **Figure 4.10** (specifications are shown in Table 4.1). For an additional capital cost of 5 USD/m², the reduction in thermal transmittance of the exposed wall elements to 0.5

Figure 4.11 Cost-benefit analysis for the detached dwelling

(Based on simulations for Santiago)



W/m²K, raised winter room temperatures to comfort with daily mean values reaching 17°C. In summer, additional insulation caused no penalties to occupant thermal comfort contributing to lower daily mean room temperatures by 1.5K. As shown for the results of the cost-benefit analysis in Figure 4.11, among the variations performed the addition of insulation was the most cost-effective in reducing energy use yielding a cost-benefit ratio of 5.3 and leading to an annual consumption below 6 kWh/m².

4.3.3 Glazing size and orientation

So far with the techniques applied in the analysis, daily temperature ranges of 15–18°C and 22–25°C have been achieved. With 70% less energy for space heating and no more than 5% in extra capital costs, adjustments to glazing areas affect the range of comfort temperatures and may be preferred by occupants. As shown in Figure 4.12, increasing the glazing-to-floor area from 10% to 18% will provide additional solar heat gains to achieve better temperatures of 15–22°C in winter and 21–26°C in summer. This increase in size of glazing elements reduces the space heating energy of the base-case dwelling by 25% (Figure 4.11) with higher room heating set-points than 17°C increasing the energy reduction rate in the order of 10% for each 1°C (see also variations in space heating energy in Figure 4.31).

Deviation in orientation of glazing surfaces from true north may be a cause of occupant thermal discomfort (Figure 4.13). An easterly or westerly orientation will lower winter daily room temperatures by 1K, and by a further 1.5K during hours of high solar radiation. In summer, a westerly orientation will be more prone to cause overheating, raising temperatures by 2–3K above comfort. However, a number of additional design measures and building controls can be used by occupants to compensate for the disadvantages of off-north orientations (see trade-off options and design alternatives in summary Table 4.2 by the end of the chapter).

4.3.4 Dwelling type

In the case of the intermediate-floor apartment, minor additional measures were needed to achieve occupant thermal comfort. Compared to the standard base-case detached dwelling the daily temperature pattern in the apartment tended to be more stable and responsive to variations in building envelope design (see results of simulations for the apartment from Figure 8.7.1 to 8.7.5, Appendix 8.5). To achieve comfort temperatures in winter, it was required nearly 25% of the total amount of additional external wall insulation and less than 75% of the glazing surfaces used for the detached dwelling (Figure 4.13). Although these measures contribute to raise room temperatures above comfort levels in summer the compensatory cooling effect of shading and ventilation was much greater and evenly distributed throughout the day (Figure 8.7.5).

Furthermore, no additional building costs were incurred to improve the standard apartment building. These resulted in one-fifth less additional capital cost than for the detached dwelling, a total of 30 USD/m² per dwelling (Figure 4.14). In fact, the additional capital required to apply the proposed improvement measures was two times lower than the actual extra capital ob-

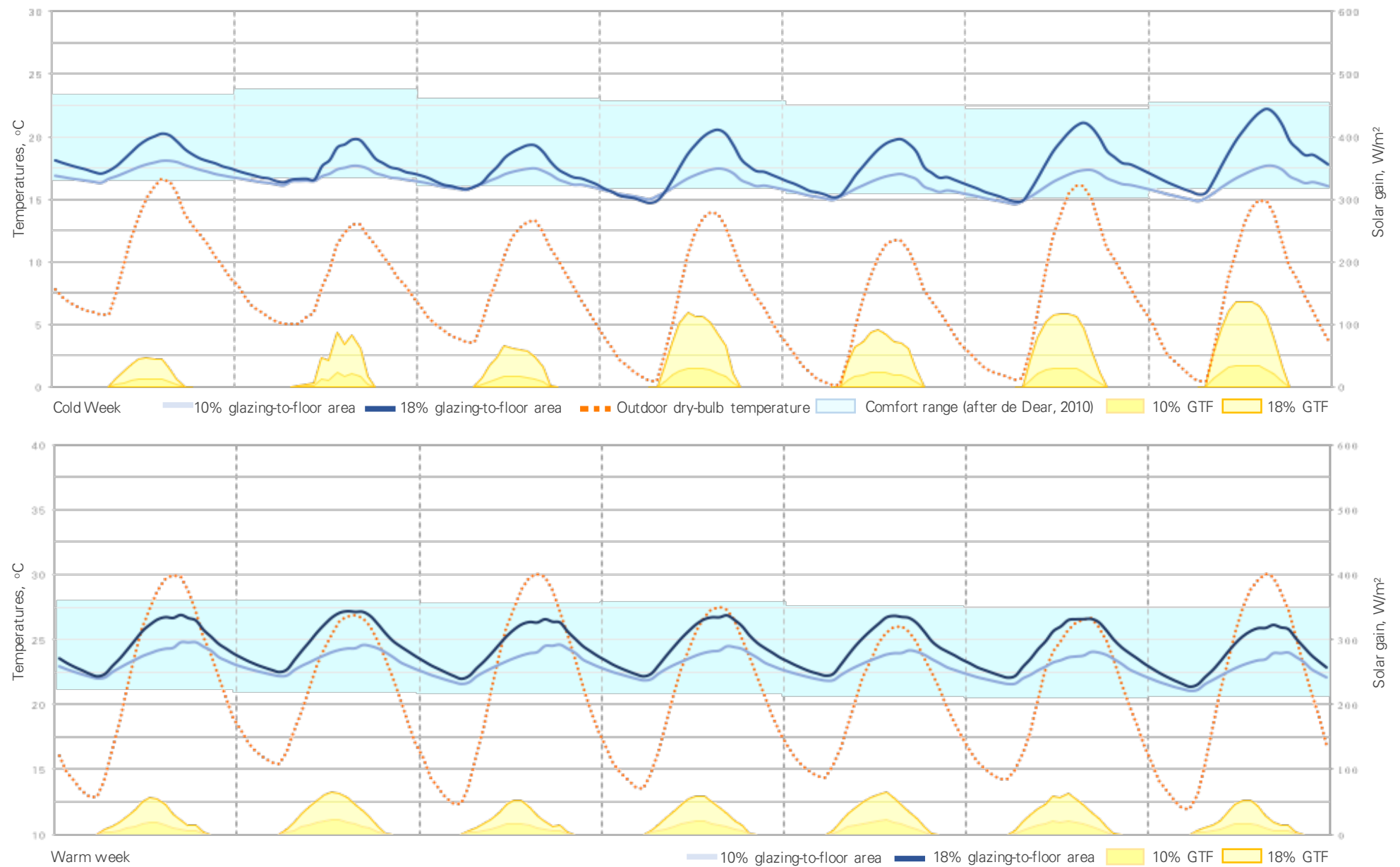


Figure 4.12 Effect of increasing the size of room glazing areas (single-storey detached dwelling)

For the windows of the base-case dwelling oriented towards the equator, room net glazing-to-floor areas are increased from 10% to 18% (based on results for the living area)

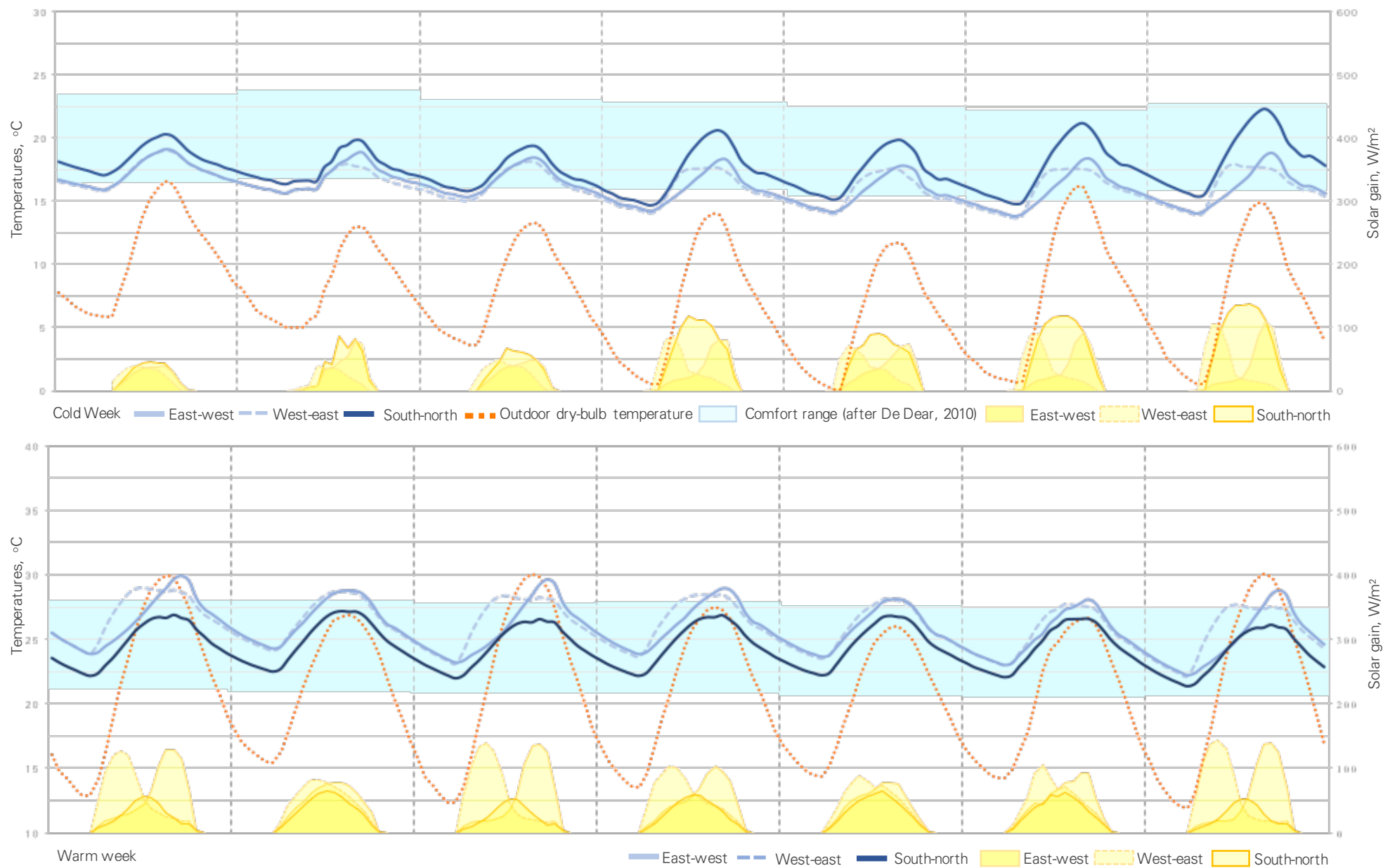


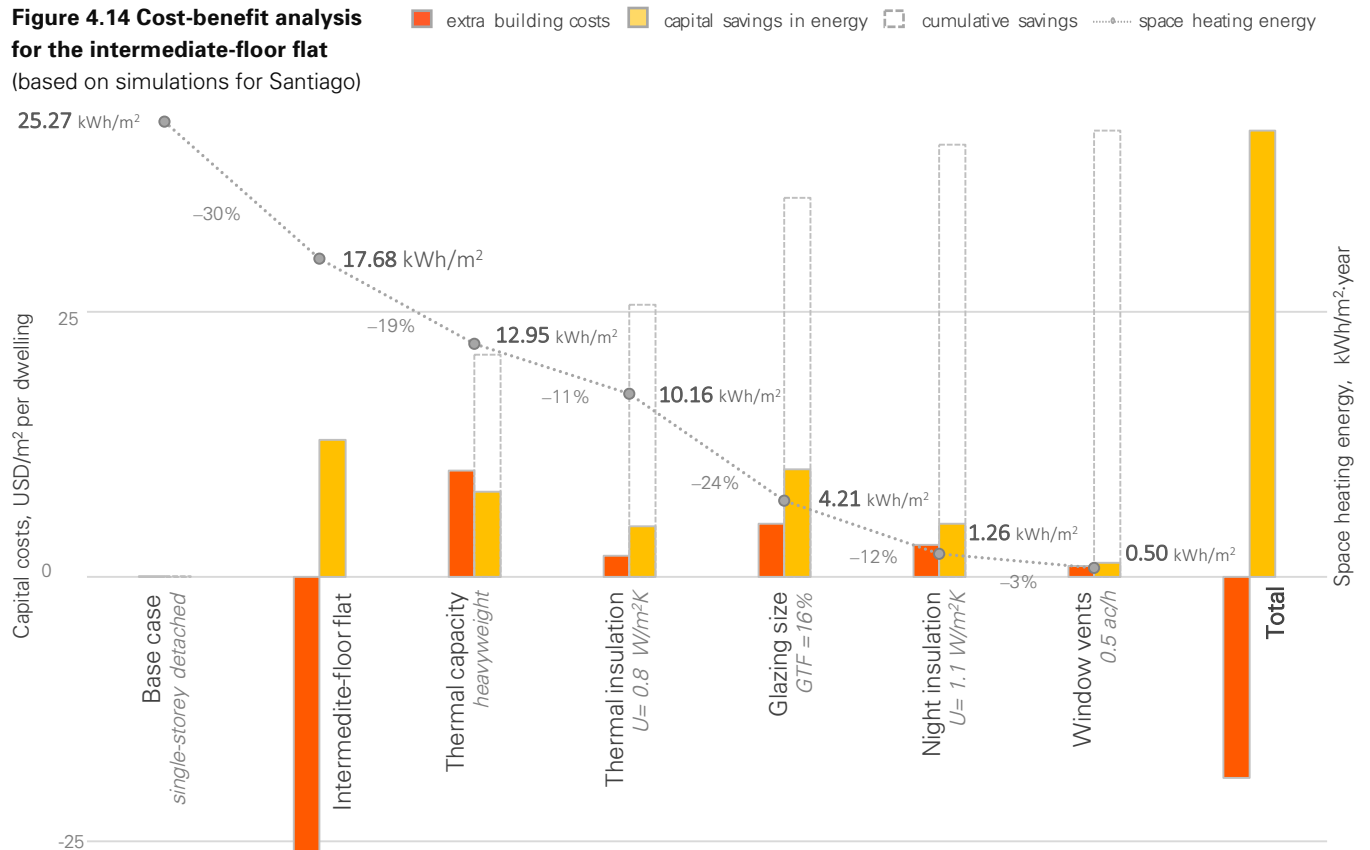
Figure 4.13 Effect of changing orientation of room window areas (single-storey detached dwelling)

The distribution of window areas in the base-case dwelling was improved to orient most of glazing areas toward the equator (based on results of simulations for the living area).

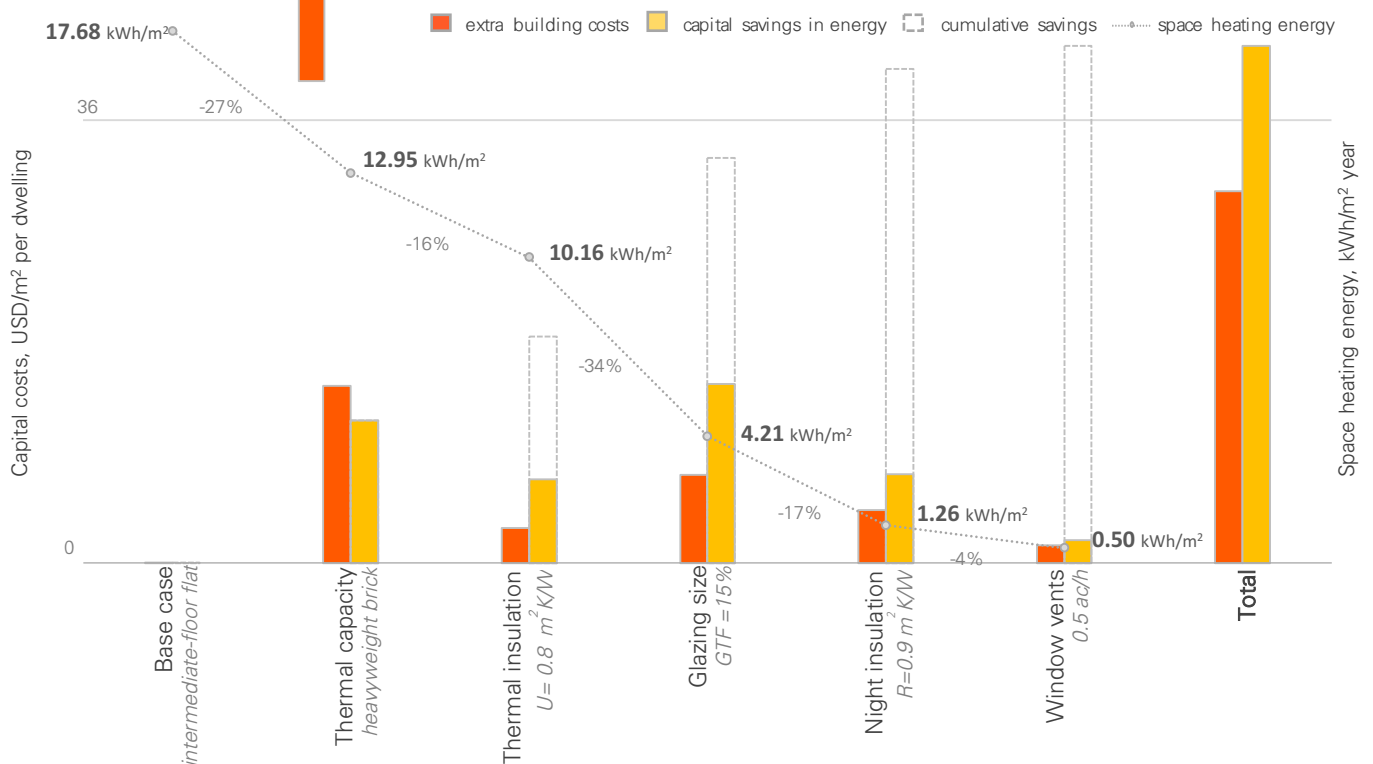
tained by building apartment accommodations instead, 60 USD/m² per dwelling. As well as a saving of 30% in energy, between the base case detached and the intermediate-floor apartment, the balance between the useful heat gains from solar radiation and heat losses through glazing becomes more be-

Figure 4.14 Cost-benefit analysis for the intermediate-floor flat

(based on simulations for Santiago)



4.13a Comparison of the base-case detached with the improved apartment



4.13b Comparison of the base-case apartment with the improved apartment

neficial —this was evidenced since five times more energy was saved in the apartment by using a third of the total glazing areas required for the detached. Having achieved energy demands below 5 kWh/m²·year, the focus of further analysis in the next section is on the extent to which the building envelope design can be adjusted to suit individual temperature requirements.

4.4 Design of Operable Envelope Elements

In dwellings where no conventional energy appliances are used for space heating and cooling daily temperature patterns depend on a number of behaviours by occupants (Humphreys et al., 2010). These are deliberate adjustments to heat and mass fluxes surrounding the human body within and around buildings. The process of thermal adaptation can be enhanced with design of different physical and spatial elements that allow occupants to remain comfortable under variable conditions (Baker and Standeven, 1997). The following is a partial account of some of these elements which can be operated separately or in combination to assist occupant maintain thermal comfort over time.

4.4.1 Insulated shutters

Figure 4.15 shows the effects of internal shutters closed over window openings during evenings and overnights (detailed specifications are shown in Table 4.1 and Figure 4.4). Increases in mean daily room temperatures of 1.5K can be observed with temperature differences reaching 2K and above during periods of highest internal heat gains from occupancy. This option should be considered with regard to the additional capital benefits for households requiring special provisions (see vulnerable occupant requirements in Chapter 2, p.23). By using fibreboard shutters with a thermal resistance of 1.1 m²K/W, the ratio of investment to capital return resulted in 1.1 with daily mean room temperatures above 18°C and space heating energy decreasing as much as to below 2 kWh/m²·year on both houses and apartment types.

4.4.2 Operable vents

Taken together the results of simulations provide substantial evidence proving that residential apartment accommodations have a greater potential for passive acclimatisation. As can be observed in the results for the apartment (see Figure 8.7.4, Appendix 8.5), variations in air-exchange rates had a more influential effect on room temperature patterns than those observed for the standard detached dwelling in Figure 4.15. Moreover, apartments located on intermediate floors showed a better potential for controlled ventilation allowing occupants adjustments in temperatures of ± 2 K during winter weeks and by over ± 4 K during midseason weeks (Figure 8.9, Appendix 8.5). As a result of minimising by half the amount of outside air intakes virtually no energy was needed to meet target daily comfort temperatures throughout the full length of the heating season (Figure 4.11, 4.14).

4.4.3 Adjustable louvers

During the cooling season, the choices for occupant thermal adaptation are much broader and favoured by variations in outdoor climate conditions. Most occupant thermal comfort problems can be avoided by minimising excess heat entering through glazed and opaque elements of the building envelope.

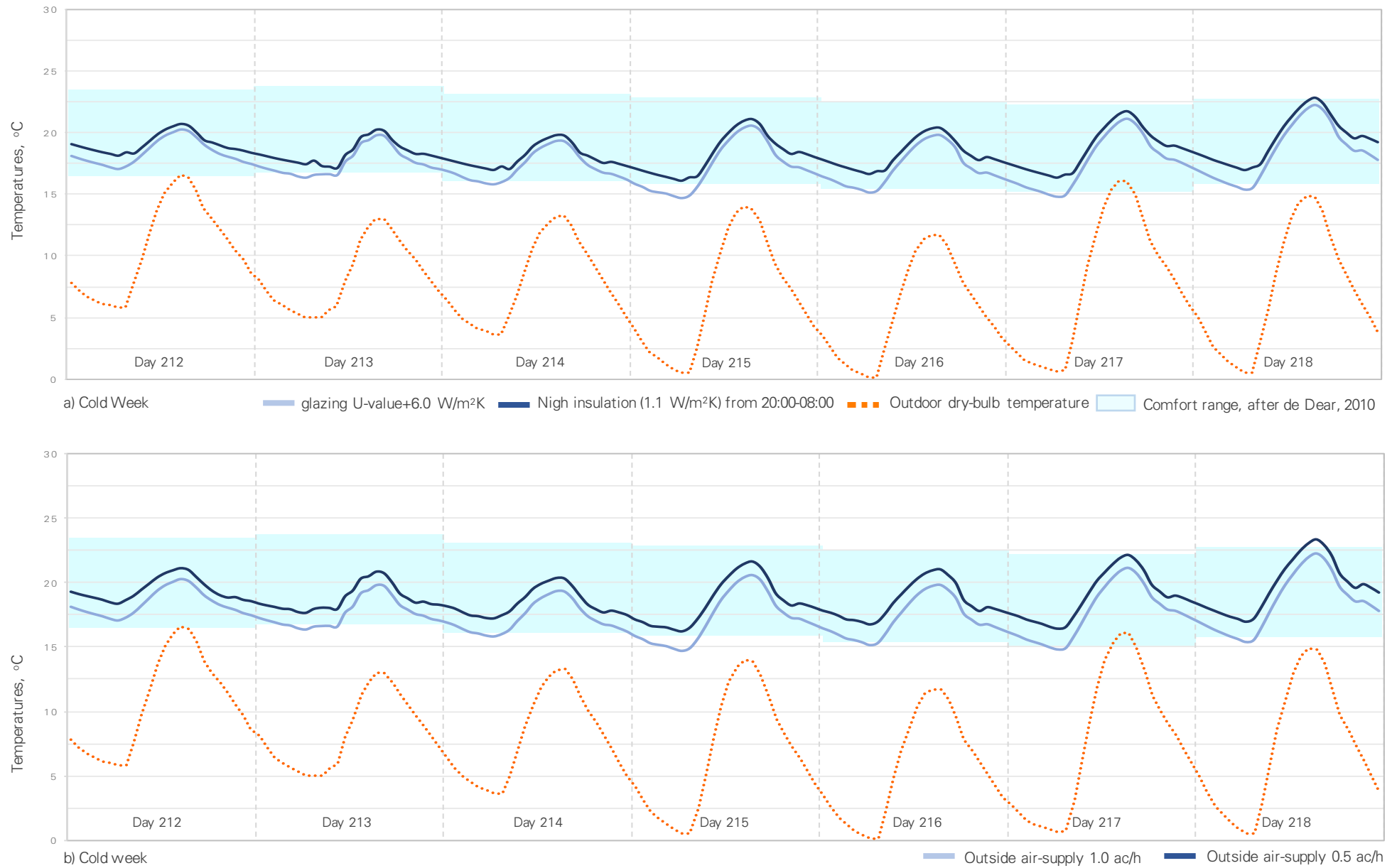


Figure 4.15 Effect of insulated shutters and window-frame vents (single-storey detached dwelling)

a) room thermal performance with and without use of internal blind shutters over night; b) outside air-supply rates are reduced by assuming window vents openings at minimum.

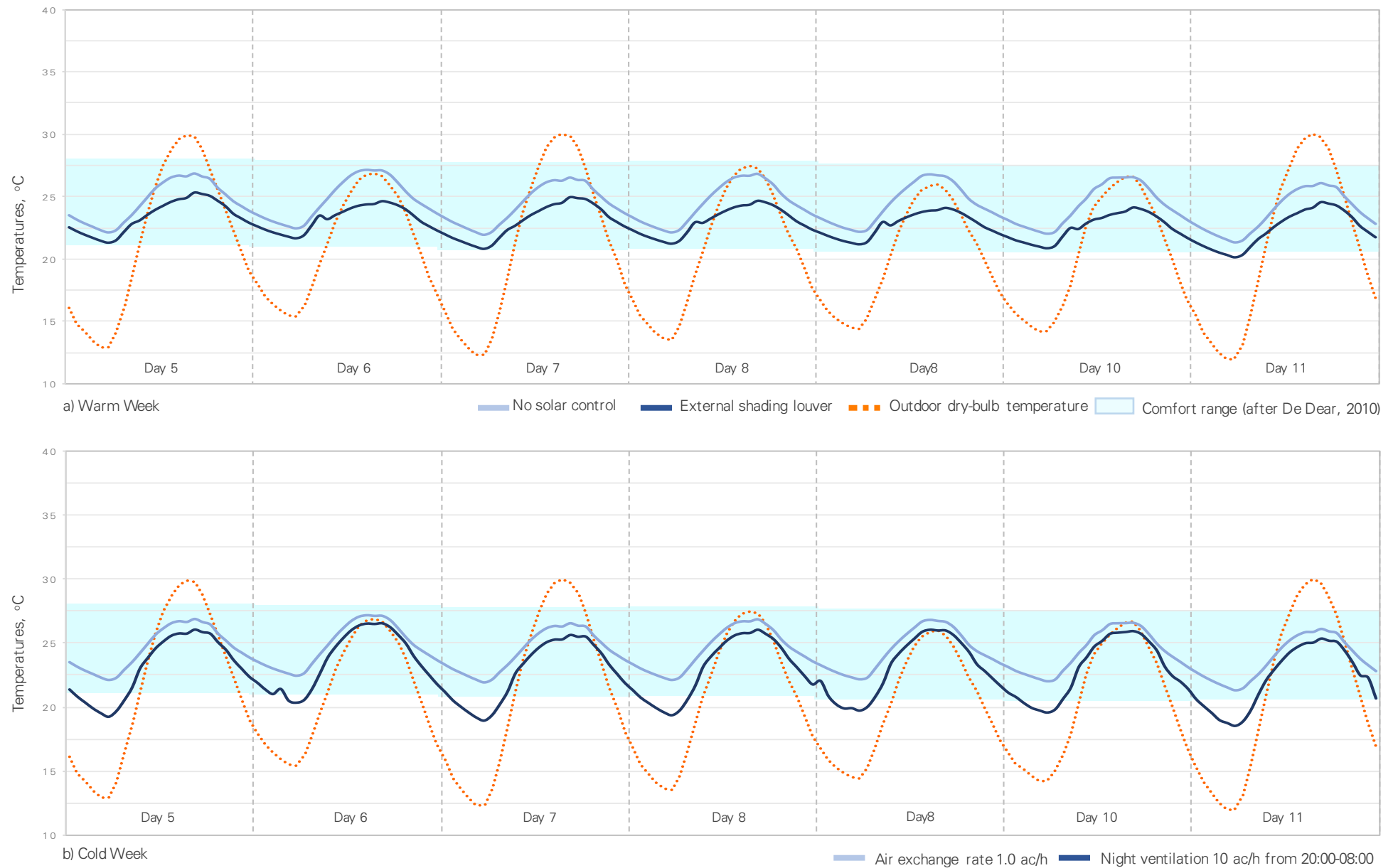


Figure 4.16 Effect of external shading blinds and opening windows (single-storey detached dwelling)

a) external window louvers are operated with their blinds positioned horizontally; b) half of room window area is assumed opened overnight, the equivalent of 10% room floor area (the resulting air exchange rate above is an average value obtained for the period over which windows were kept opened).

As shown in **Figure 4.16**, the effect of using exterior shading blinds is significant, improving occupant thermal comfort, lowering room temperatures by 3K during periods of high outdoor temperatures and sunshine levels (see Table 8.15 in Appendix 8.5 for detailed specifications and input parameters). The lower envelope exposure of the apartment to outdoor air temperatures and solar heat contributed to cooling, reducing daily mean room temperatures by 4K uniformly over evenings and nights (Figure 8.7.5, Appendix 8.5).

4.4.4 Openable Windows

Cool night-time temperatures and evening breezes are well-known sources for passive cooling of dwellings in central valley locations (Muller, 2006; Roland et al., 2008). From the results of simulations, the operation of windows was identified as a primary source of occupant adaptation to day-to-day changes in outdoor climate conditions. Over most of the year, the control of heat losses and excess heat dissipation through opening and closing of windows allow adjustments in room temperatures of over $\pm 4\text{K}$ (**Figure 4.16**). However, during warmest summer days, when daytime temperatures rise above comfort, windows are better kept closed. During evenings the opening of windows will help cooling rooms by 4–8K. As shown in Figure 4.16, with 25% of window areas opened, the equivalent of 5% of room floor area, comfort temperatures can be maintained through all of the cooling season.

4.4.5 Naturally Conditioned Dwellings

Under extreme cold and warm outdoor conditions, adequate control of room temperatures can be still achieved by combining use of different passive operation techniques. **Figure 4.17** shows an hour-by-hour annual distribution of room temperatures resulting by adjusting building passive control parameters as a function of day-to-day changes in outdoor temperatures. During coldest months when outdoor temperatures peak below 0°C , room daytime temperatures can be kept above 16°C by minimising excess ventilation and closing insulated shutters overnight. During warmest months when outdoor temperatures peaks at 35°C , room temperatures can be maintained below 27°C by combining use of exterior shading and adequate night ventilation. From the annual graphs in Figures 4.17 and 4.18, it is proven that operable envelope elements are highly effective for control of room temperatures indicating that further design stages should focus on increasing the array of options and user responsiveness through careful element specification.

For the most and least exposed dwelling type simulations show that occupant thermal comfort can be achieved under free-running conditions all year-round (Figure 4.17, 4.18) at little extra capital cost. In the case of the detached dwelling most of the additional building costs (40%) and savings in space heating energy (75%) are incurred in increasing the thermal capacity and insulation of the building envelope (Figure 4.11). As shown in **Figure 4.19**, during the cold day room temperatures drift above 17°C reaching 20°C during peak occupied hours while offering additional temperature adjustments of 1.5K through controlled ventilation and use of night shutters. During the warm day, the use of exterior shading was sufficient to maintain daytime temperatures below 25°C as well as extra 3K through night ventilation. The

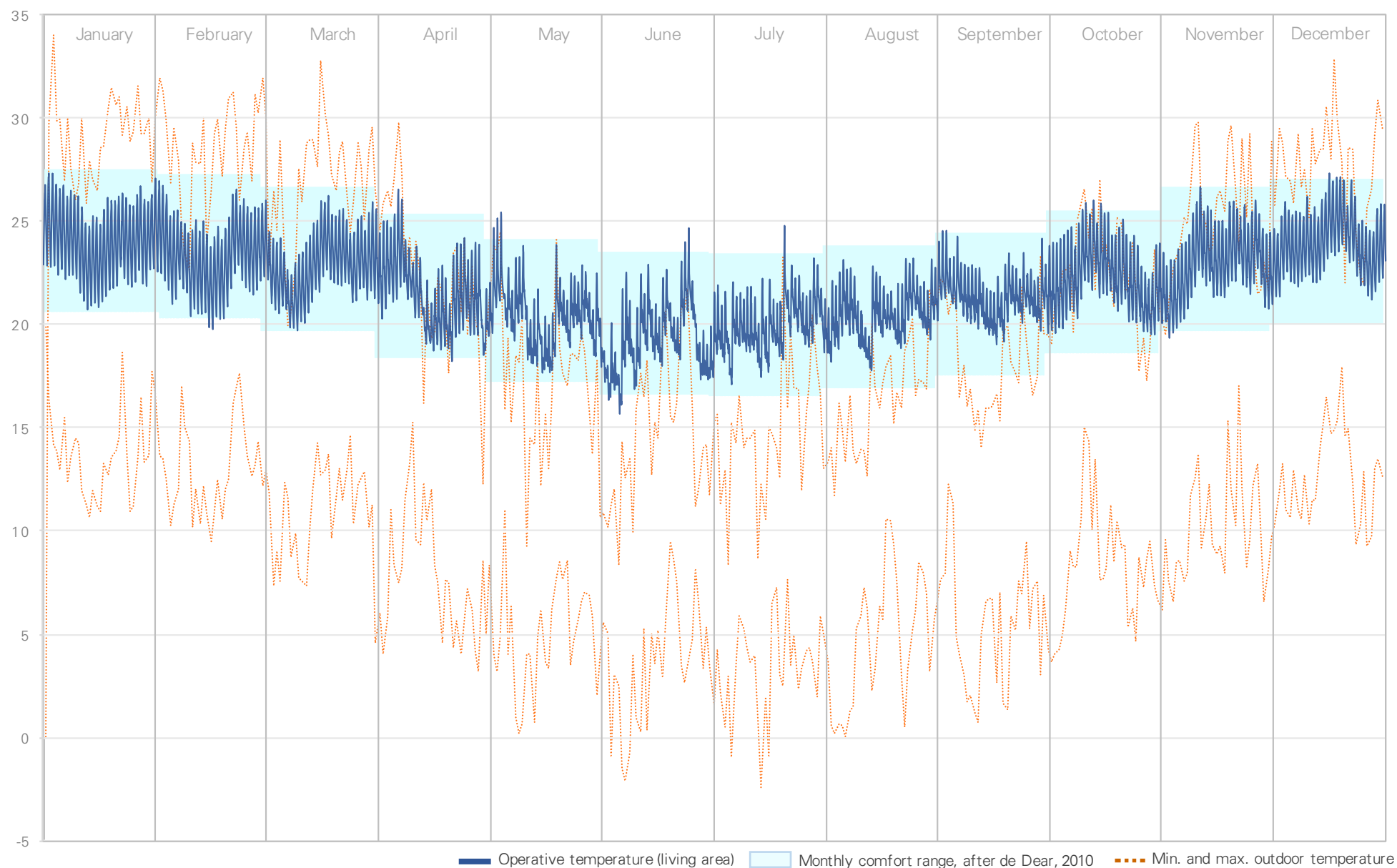


Figure 4.17 Resultant indoor temperatures for naturally conditioned dwellings (single-storey detached)

The graph is based on fixed envelope properties for exposed walls, roof and floor elements, as specified for Santiago in Figure 4.30, and variable monthly settings for operable envelope elements (night shutter, window-frame vents, exterior shading and window openings). Further day-to-day adjustments can be made by the occupants if required.

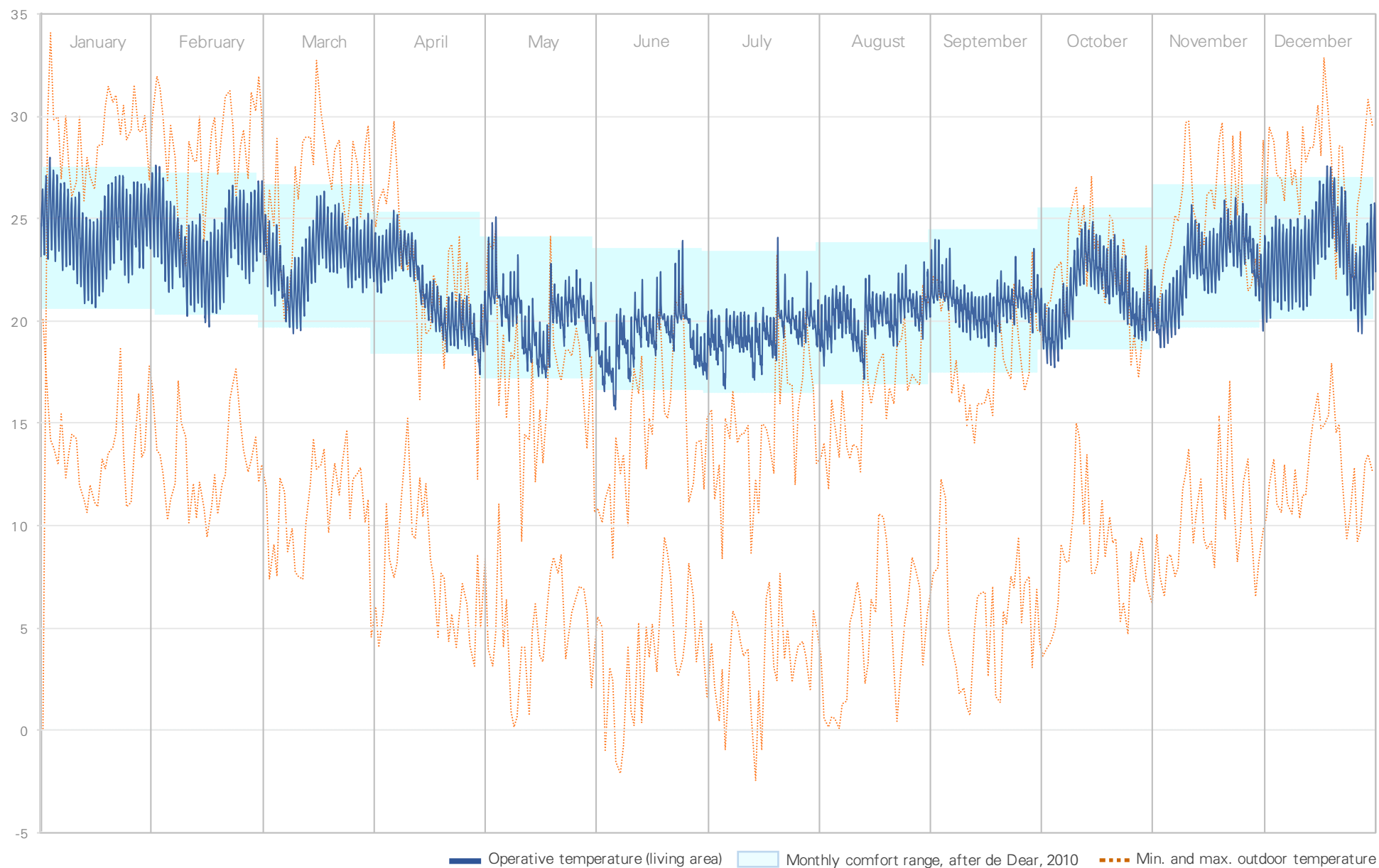


Figure 4.18 Resultant indoor temperatures for naturally conditioned apartments (intermediate-floor flat)

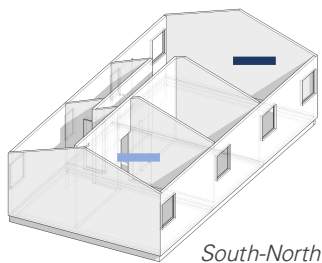
The graph is based on fixed envelope properties for exposed walls, roof and floor elements, as specified for Santiago in Figure 4.30, and variable monthly settings for operable envelope elements (night shutter, window-frame vents, exterior shading and window openings). Further day-to-day adjustments can be made by the occupants if required.

additional capital cost of improving the standard detached dwelling was estimated at 36 USD/m² per dwelling, 8.8% of the minimum housing budget allocated by the government, while capital savings in running space heating energy cost were valued at 440 USD per year.

For the intermediate-floor apartment, savings in space heating energy in the order of 60% resulted from improvements to glazing and window components. Winter room temperatures in the improved apartment varied between 17–24°C, but with choice for additional temperature adjustments of 2K (see Figure 8.7.4, in Appendix 8.5). In summer daily room indoor temperatures were kept within 20–27°C with an additional reduction of 4K achievable through opening windows (Figure 8.7.5, Appendix 8.5). The cost benefit ratio

Figure 4.19 Performance of the improved detached dwelling

Brick masonry dwelling: insulated shutter used for the cold day and shading and window openings for the warmer day



WTF : 18%
HLC : 3.9 W/K m²
infiltration : 1.0 ach
ventilation : 8.0 l/s/p

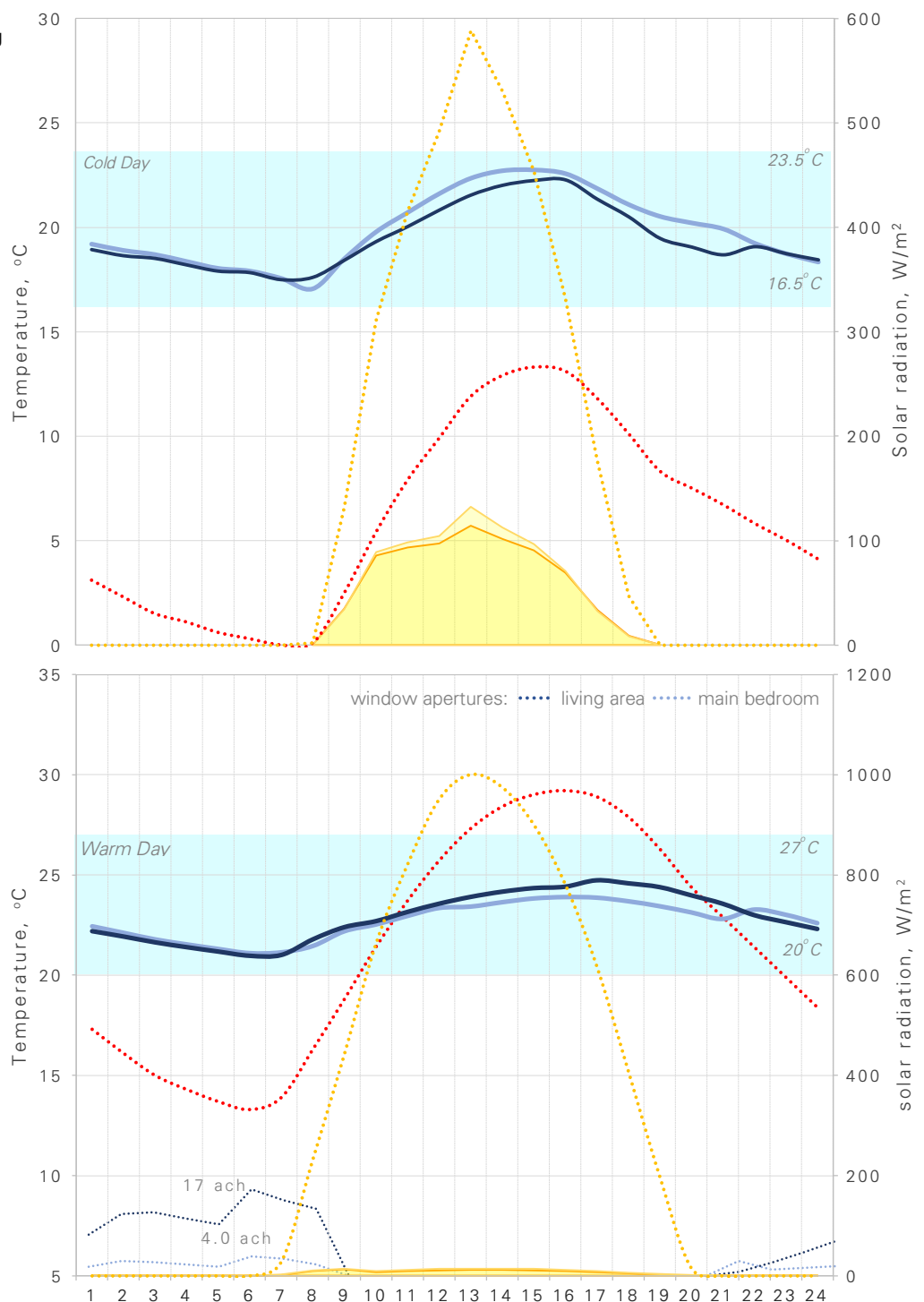
Thermal transmittance, W/m²K

roof : 0.4
external walls : 0.5
windows : 5.8
windows + internal blind : 1.1
ground floor : 1.1

Occupancy heat gains, W/m²

07-15 hrs. occupants (1) : 5.0
equipment : 5.0
15-19 hrs. occupants (3) : 15
equipment : 5.0
19-23 hrs. occupants (4) : 20
equipment : 10
23-07 hrs. occupants (4) : 20
equipment : 5.0

- living area
- main bedroom
- outdoor temperature
- daily comfort range (after de Dear 2010)
- global solar radiation
- solar gain living area
- solar gain bedroom

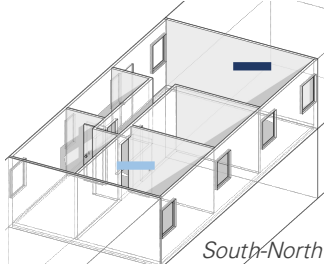


of the improved apartment building is 3.2 with an extra use in construction capital of 27 USD/m² per dwelling with respect to the base-case dwelling. There are strong indicators showing that the current increase in construction of apartments should be regarded as an opportunity for developing a more resilient stock of residential buildings capable of responding to changes in outdoor climates, domestic energy use and imported fuel prices (ECLAC, 2014).

From this point onwards the question of how much energy can be saved in dwellings becomes a matter of individual choices and habits. From one household to another, variations in type of heating system, operation schedules and thermostat settings will have the largest effect on energy consumption (see variations in space-heating energy in Figure 4.31). As an indication, annual energy savings of 25 kWh/m² achieved above, translate into monthly

Figure 4.20 Performance of the improved apartment flat

Brick masonry dwelling: insulated shutter used for the cold day and shading and window openings for the warmer day.



WTF	: 16%
HLC	: 2.6 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

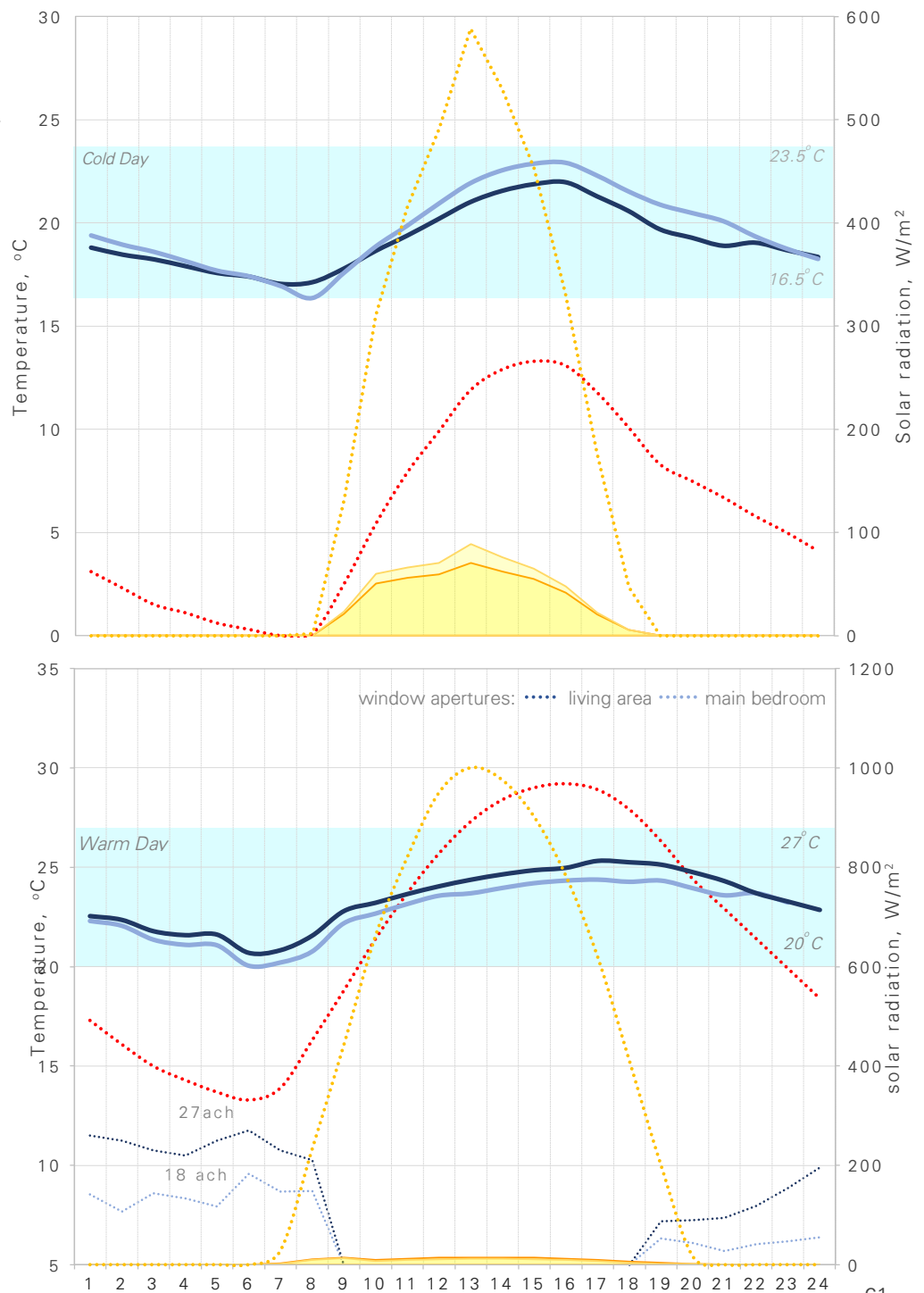
Thermal transmittance, W/m²K

roof	: -
external walls	: 0.5
windows	: 5.8
windows + internal blind	: 1.1
ground floor	: -

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

- living area
- main bedroom
- outdoor temperature
- daily comfort range (after de Dear 2010)
- global solar radiation
- solar gain living area
- solar gain bedroom



capital amounts as large as 40–50% of the median poorest household quintile (CASEN, 2013). On the other extreme, in middle and richest income groups where central heating systems are generally operated under continuous 20°C, the amount of energy saved can be as much as 95 kWh/m²·year — deduced from an initial demand of 100 kWh/m² and an improved scenario reaching 5 kWh/m² (Figure 4.31). The design strategies proposed have then an ample scope of application to improve the design of new housing stock in central regions of Chile with relative large implications on household capital expenditures, space heating energy and harmful pollutant emissions.

4.5 Regional Design Variations

To achieve the target performance criteria for other regions across the country differences in outdoor climate conditions were compensated for changes to building design parameters (see summary of regional design variations in Figure 4.30). Provided that the thermal capacity of improved dwelling designs helped moderate diurnal outdoor temperature swings in the central interior region variations in seasonal outdoor temperatures along the north-south axis of the country were offset by adjusting building envelope heat losses. As explained in more detail below, this was performed by adjusting the thermal insulation of exposed opaque elements, limiting the size of glazing, and specifying better insulated shutters, shading and/or ventilation devices (see graphical overview of design variations in Figure 4.5). Through different combinations of such measures, where appropriate, the design techniques proposed can be adapted to build naturally conditioned dwellings across the main inhabited region of the country incurring minor or no penalties on occupant thermal comfort and space heating energy.

4.5.1 Northern Chile

The climate along the coast, where most of the northern population resides, is characterised by warmer heating and cooling seasons compared to those of the central interior region. For example, the coastal location of Antofagasta (20°S) has smaller fluctuations in diurnal outdoor temperatures compared to Santiago but higher amounts of outdoor solar radiation. During cold and warm days, peaks in outdoor dry-bulb temperature vary between 10–15°C and 18–25°C and peaks in global solar radiation between 0.8–1.2 kWh/m² (see daily monthly average distribution in Appendix 8.5, Figure 8.4.2). While compared to southern regions the likelihood of thermal discomfort and space heating energy consumption in winter is considerably lower in residential dwellings the occurrence of overheating can be a recurrent problem over the year.

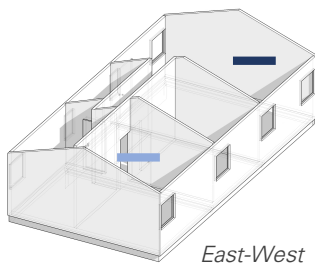
The poor performance of the standard base-case dwellings in the north of the country adds evidence that the national regulations have a poor record in improving thermal comfort. The results of the base-case detached dwelling for the cold day in **Figure 4.21** show that although winter underheating was less severe than in southern regions, room temperatures fell below 15°C during mornings and late evenings. Space heating energy rose to 12 kWh/m² or above depending on the heating system in use (Figure 4.31). On a warm day, peak temperatures exceeded 30°C and the extent of overheating was greater by also affecting the morning. Unlike the occurrence of underheating which arises over few winter weeks, overheating prevailed as a dominant problem

taking place over the summer and most midseason weeks. The prevalence of occupant thermal discomfort due to overheating can be more clearly distinguished from the results of the base case apartment which shows considerably higher temperatures during both seasons (Figure 4.22).

In winter, the risk of underheating in the base case apartment flat was significantly reduced compared to the detached house as room temperatures drifted within comfort limits over most of the day and space heating energy decreased to 7.5 kWh/m² year. In contrast, over the cooling season, severe overheating conditions were observed as room temperatures peaked above 35°C. Therefore, in response to the warmer outdoor temperatures of Antofagasta, the heat loss coefficient of improved dwellings was increased by reducing the insulation of exposed opaque elements and increasing the size of

Figure 4.21 Performance of the base-case detached dwelling

Timber-frame dwelling specified with minimum insulation and glazing size for Antofagasta. Other than windows (kept closed), no other operable element is in use.



WTF	: 10%
HLC	: 7.7 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

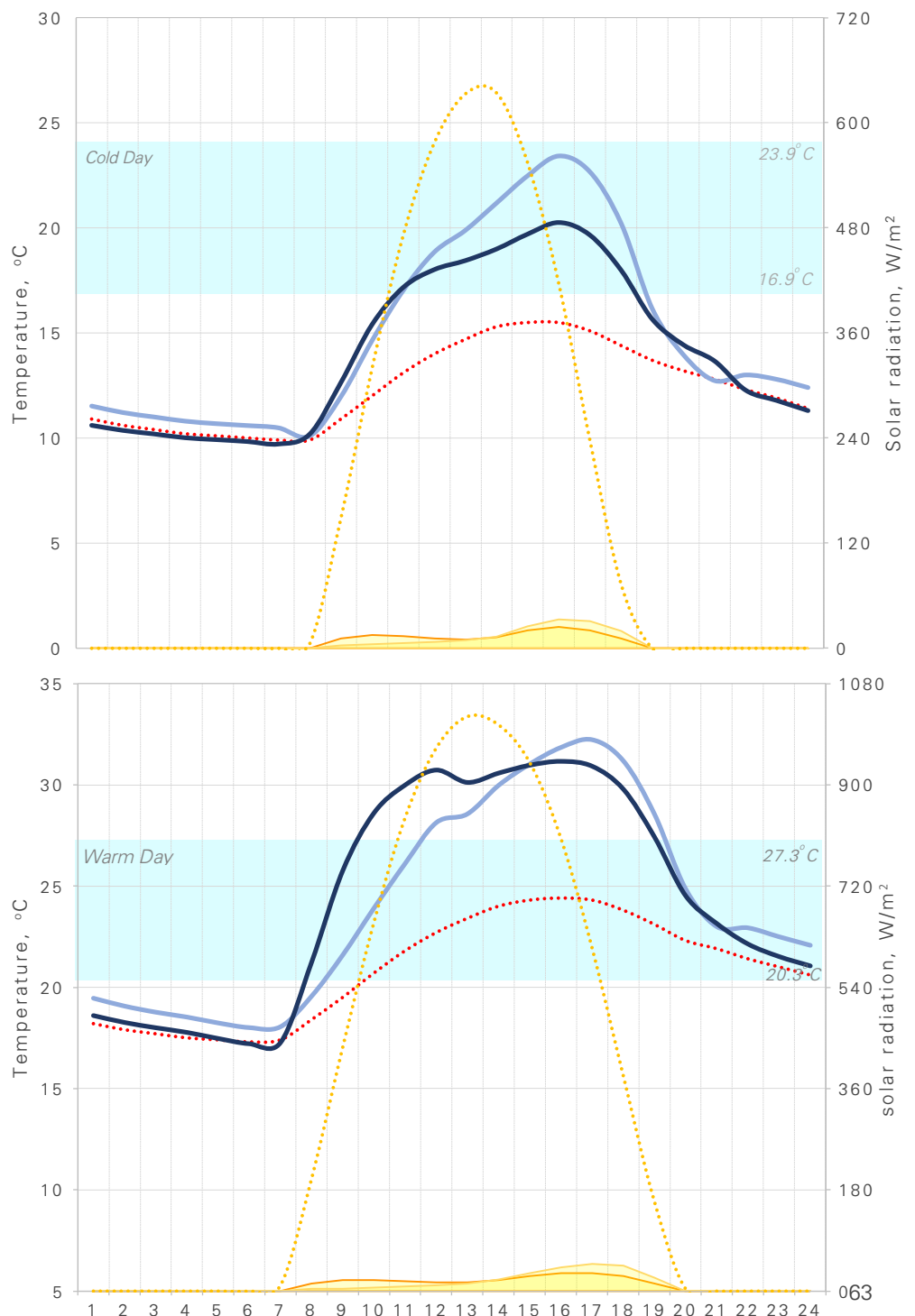
Thermal transmittance, W/m²K

roof	: 0.8
external walls	: 4.0
windows	: 5.8
ground floor	: 1.1

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

- living area
- main bedroom
- ... outdoor temperature
- daily comfort range (after de Dear 2010)
- ... global solar radiation
- solar gain living area
- solar gain bedroom

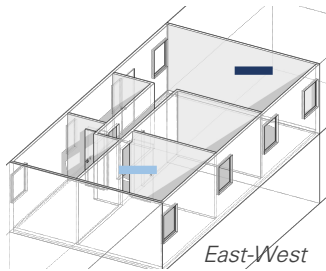


glazing (step-by-step parametric simulations for Antofagasta are depicted in full-page graphs on Appendix 8.5, from Figure 8.18 to 8.20).

It can be seen from the results of simulations from Figure 8.9 to Figure 8.10 in Appendix 8.5, that compared to the central regions no significant differences were encountered in terms of building design. As shown for the detached house in Figure 8.9.1, the effect of increasing the heat storage capacity of the building structure decreased by 2.5K. However, by applying less wall insulation and by increasing glazing areas, winter comfort temperatures were met without recourse to insulated shutters nor additional airtightness measures (Figures 8.9.2 and 8.9.3). Over the warmer period, the use of exterior shading and half of the window area kept opened overnight and during

Figure 4.22 Performance of the base-case apartment flat

Multi-storey timber-frame building specified with minimum insulation and window size for Antofagasta. Other than windows (kept closed), no other operable element is used



WTF	: 10%
HLC	: 5.6 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

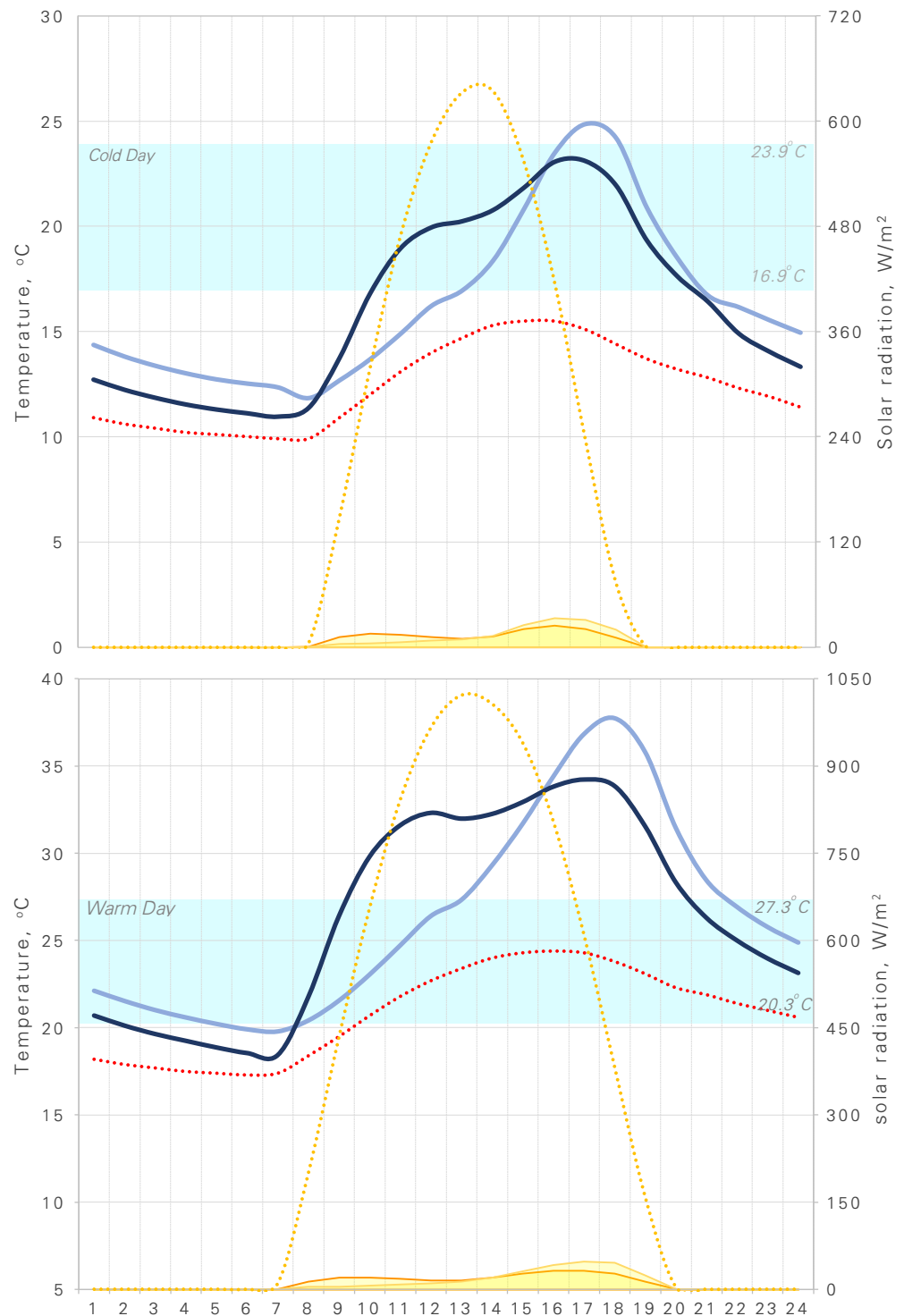
Thermal transmittance, W/m²K

roof	: -
external walls	: 4.0
windows	: 5.8
ground floor	: -

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

- living area
- main bedroom
- ... outdoor temperature
- daily comfort range (after de Dear 2010)
- ... global solar radiation
- solar gain living area
- solar gain bedroom

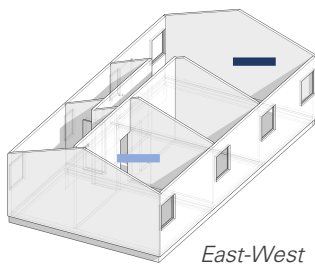


daytime were proved effective for passive cooling (Figure 8.9.5).

Overall, it can be concluded that for the northern region there is a wide range of affordable alternatives for achieving comfort in naturally conditioned dwellings. In the case of the apartment, opting for the heavyweight structure was sufficient in itself to achieve winter and summer comfort temperatures (Figure 8.10.1). In fact, other than the minimum national regulations, no additional insulation was needed to attain thermal comfort conditions other than increasing glazing size accordingly (Figure 8.10.2). Confirming the trend that

Figure 4.23 Performance of the improved detached dwelling

Brick masonry construction: exterior shading devices and window openings used for the warm day.



East-West

WTF	: 20%
HLC	: 5.9 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

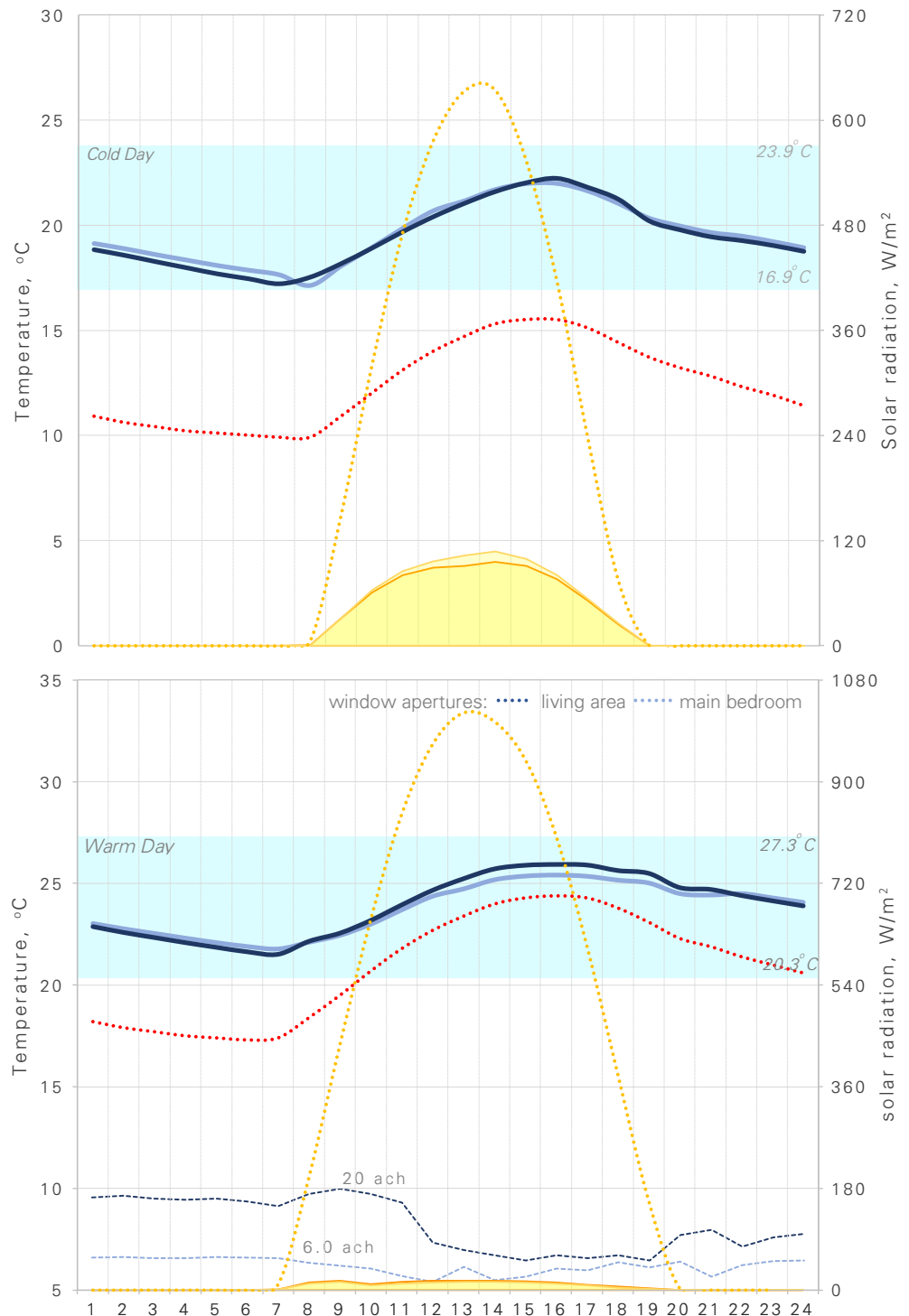
Thermal transmittance, W/m²K

roof	: 0.8
external walls	: 2.0
windows	: 5.8
ground floor	: 1.1

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

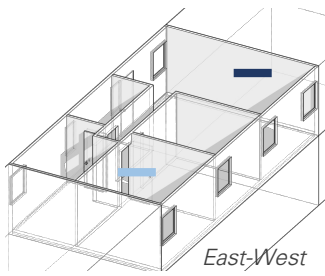
- living area
- main bedroom
- outdoor temperature
- daily comfort range (after de Dear 2010)
- global solar radiation
- solar gain living area
- solar gain bedroom



apartments are more suitable for passive occupant operation, the effects of shading and ventilation were stronger compared to the detached house (Figure 8.10.3). The extra capital cost of improving dwellings was no more than 24 USD/m² per unit whereas savings in space-heating energy ranged 200-380 USD annually (see summary of costs and extra costs in Table 6.1 by the conclusion section).

Figure 4.24 Performance of the improved apartment flat

Brick masonry construction: exterior shading devices and window openings used for the warm day.



WTF	: 18%
HLC	: 4.4 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

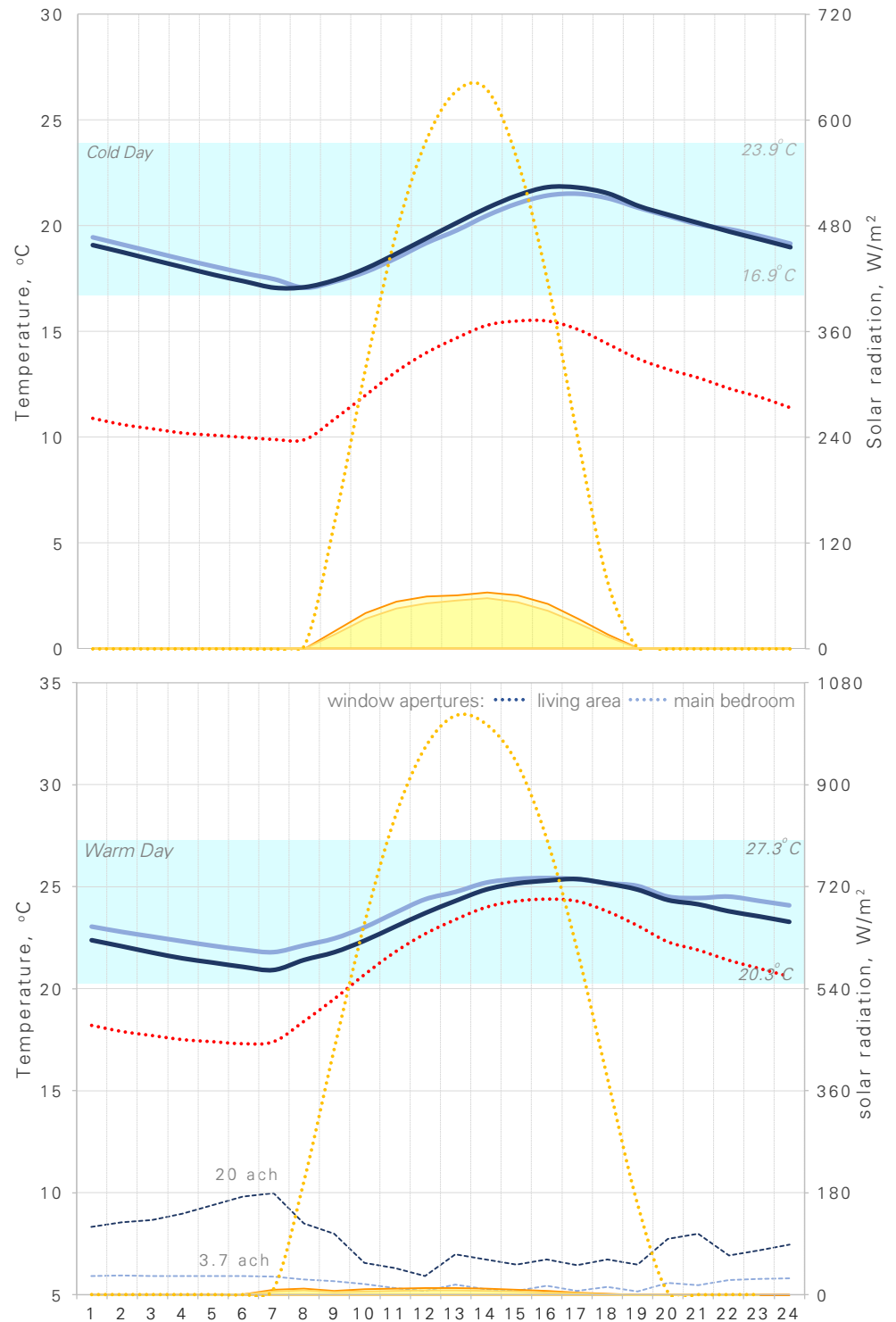
Thermal transmittance, W/m²K

roof	: -
external walls	: 4.0
windows	: 5.8
ground floor	: -

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

- living area
- main bedroom
- outdoor temperature
- daily comfort range (after de Dear 2010)
- global solar radiation
- solar gain living area
- solar gain bedroom

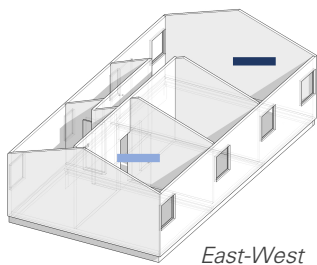


4.5.2 Southern Chile

In southern regions while the length and intensity of the heating season are greater than in the centre and north regions the likelihood of overheating decreases. Indoor occupant thermal comfort was assessed for the coastal location of Puerto Montt (41°S) which compared to Santiago has smaller outdoor temperature ranges but lower daytime temperature peaks and sunshine levels. During cold and warm days, peaks in outdoor dry-bulb temperature range between 5–10°C and 5–20°C, and peak global solar radiation between 0.3–0.8 kWh/m² (see daily monthly average distribution in Appendix 8.5, Figure 8.4.3). The dominant thermal comfort problem in standard dwellings of southern lo-

Figure 4.25 Performance of the base-case detached dwelling

Timber-frame dwelling specified with minimum insulation and glazing size for Puerto Montt. Other than windows (kept closed) no other operable element is in use.



WTF	: 10%
HLC	: 3.9 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

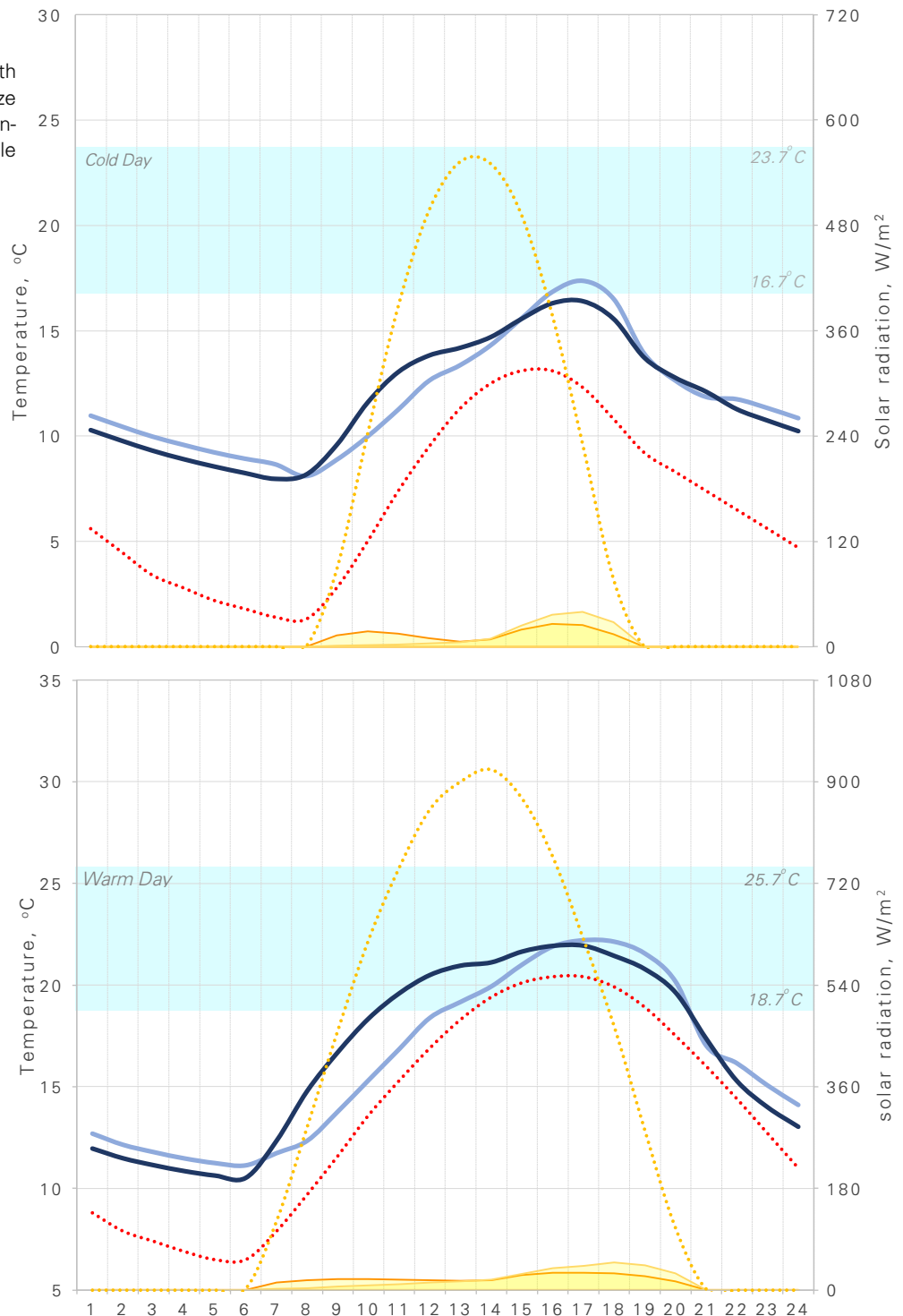
Thermal transmittance, W/m²K

roof	: 0.3
external walls	: 1.1
windows	: 5.8
ground floor	: 0.9

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

- living area
- main bedroom
- ... outdoor temperature
- daily comfort range (after de Dear 2010)
- ... global solar radiation
- solar gain living area
- solar gain bedroom

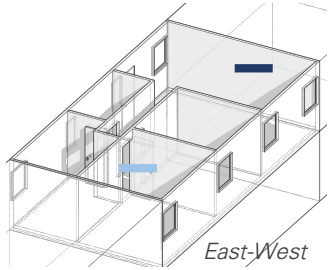


cations is the extent of underheating which take place over most of winter and midseason months, and even frequently over the summer. The negative implications of adopting minimum statutory regulation standards in these regions had the largest effect on space-heating energy, household capital, and polluting emissions from conventional combustion appliances.

As shown in Figure 4.25 during the cold day, the room temperatures of the base case detached dwelling did not rise above 17°C, but remained nevertheless above 10°C. This difference in diurnal temperature range during cold days translates into lower daily heating energy demands compared to Santiago, notwithstanding that over the full length of the heating season the total amount of energy will double reaching 50 kWh/m² year (Figure 4.29).

Figure 4.26 Performance of the base-case apartment flat

Multi-storey timber-frame building specified with minimum insulation and window size for Puerto Montt. Other than windows (kept closed), no other operable element is used



WTF	: 10%
HLC	: 2.6 W/K m ²
infiltration	: 1.0 ach
ventilation	: 8.0 l/s/p

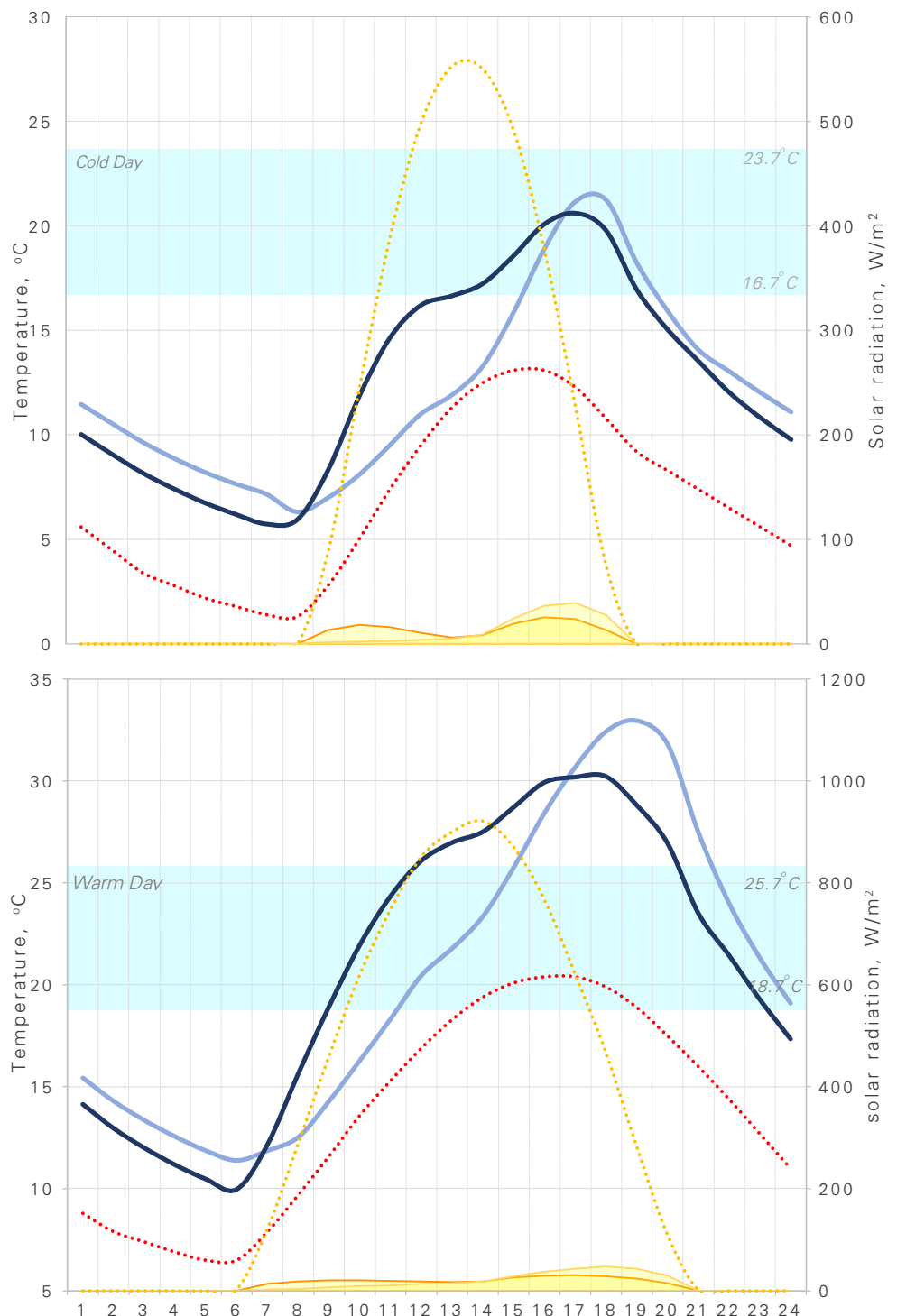
Thermal transmittance, W/m²K

roof	: -
external walls	: 1.1
windows	: 5.8
ground floor	: -

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

- living area
- main bedroom
- ... outdoor temperature
- daily comfort range (after de Dear 2010)
- ... global solar radiation
- solar gain living area
- solar gain bedroom

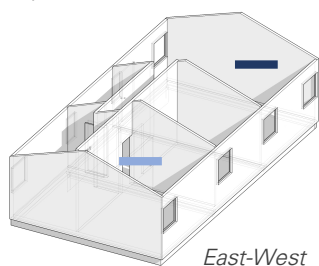


During summer, room temperatures tended to follow those outside peaking around 23°C at noon and falling below comfort overnight and early morning. Since outdoor temperatures tend to remain below comfort over most of the year, the main design concern in southern regions is the control of heat losses through improved airtightness, outdoor air-supply and/or thermal insulation of exposed envelope elements.

As in other locations, the base case intermediate-floor apartment presented significant advantages in terms of overall thermal performance. However, during cold days this advantage was less evident as room temperatures in the apartment were raised by no more than 0.5–1K above those of the de-

Figure 4.27 Performance of the improved detached dwelling

Brick masonry dwelling: insulated shutter used for the cold day and window openings for the warmer day.



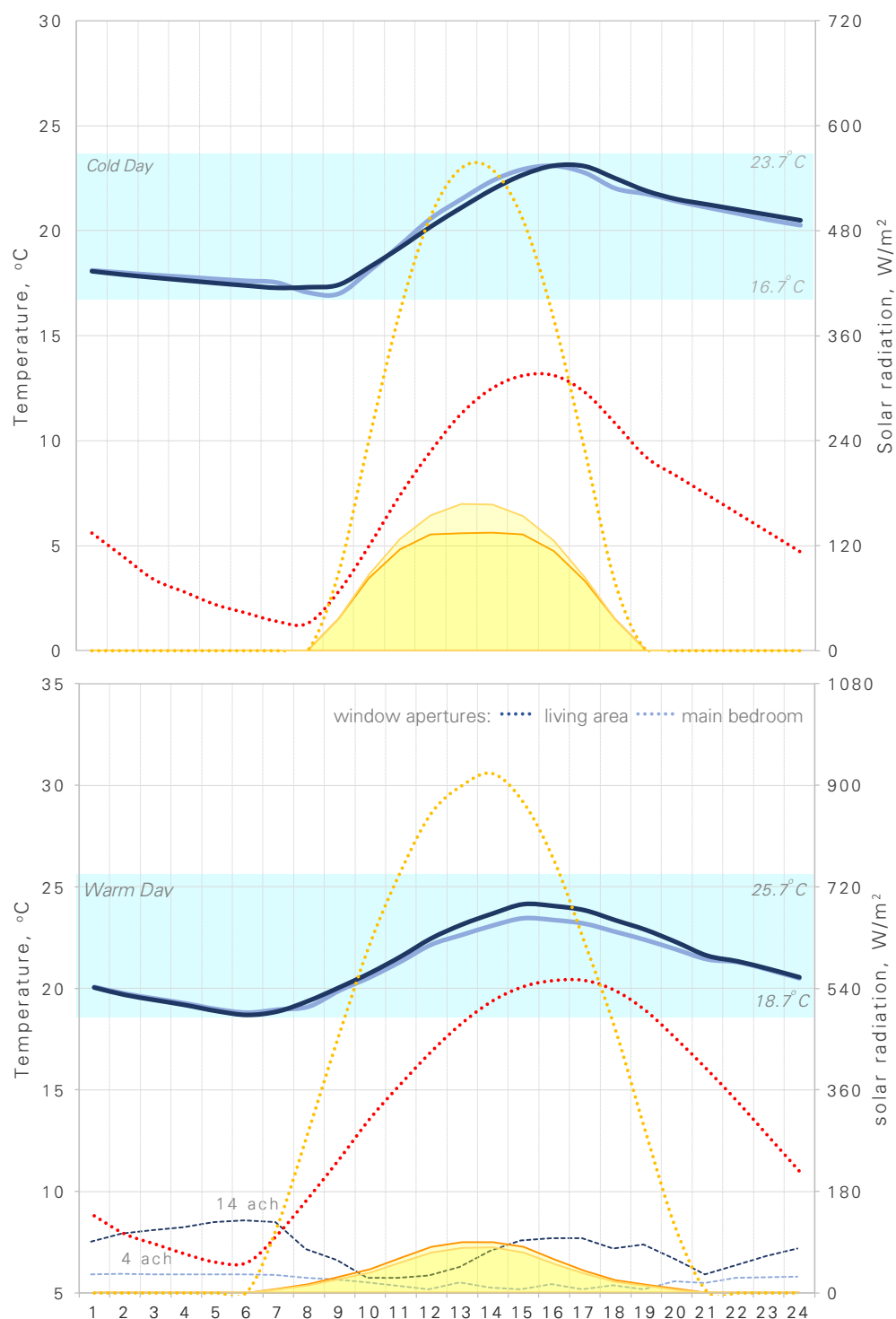
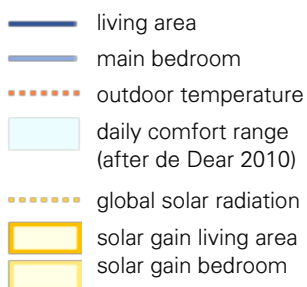
WTF : 16%
HLC : 2.6 W/K m²
infiltration : 0.5 ach
ventilation : 5.0 l/s/p

Thermal transmittance, $\text{W/m}^2\text{K}$

roof	: 0.3
external walls	: 0.3
windows	: 5.8
ground floor	: 0.5

Occupancy heat gains, W/m²

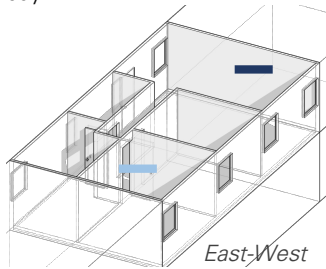
07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0



detached house (Figure 4.26). As the outdoor temperature increased towards the end of the heating season, this temperature difference became progressively larger leading to lower energy demand of the apartment which resulted in 35 kWh/m² year. Consistent with this trend, during warmer days the temperature difference increased to 5K leading to slight overheating with room temperatures rising above comfort and peaking at around 27°C in the afternoon. As evidenced by the simulations, changes in building envelope design will have a larger effect on the thermal performance of the apartment reducing the extra capital costs required to attain acceptable room temperature conditions with low energy and combustion emissions.

Figure 4.28 Performance of the improved apartment flat

Brick masonry dwelling: insulated shutter used for the cold day and window openings for the warmer day.



WTF	: 14%
HLC	: 2.0 W/K m ²
infiltration	: 0.5 ach
ventilation	: 5.0 l/s/p

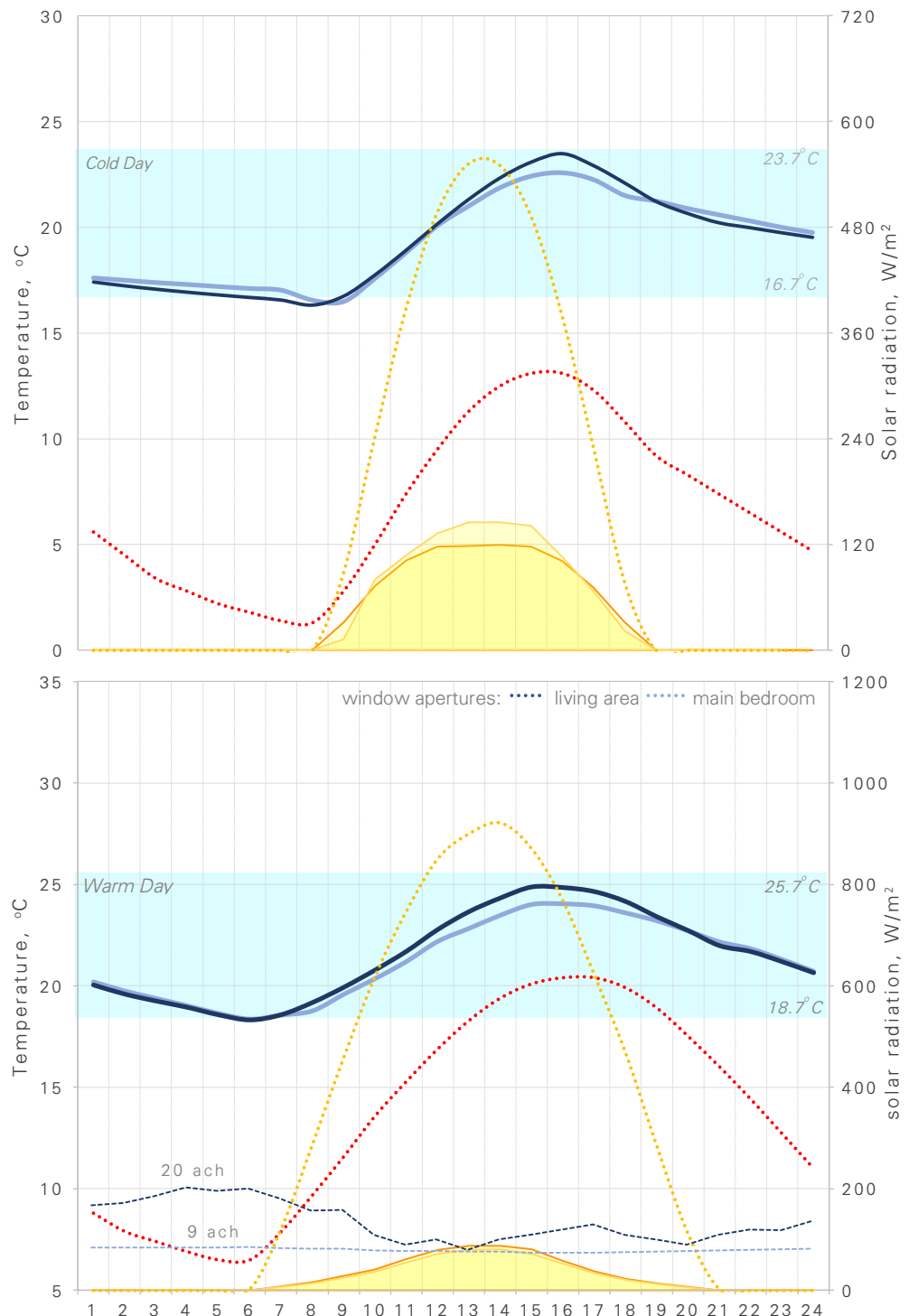
Thermal transmittance, W/m²K

roof	: -
external walls	: 0.6
windows	: 5.8
ground floor	: -

Occupancy heat gains, W/m²

07-15 hrs. occupants (1)	: 5.0
equipment	: 5.0
15-19 hrs. occupants (3)	: 15
equipment	: 5.0
19-23 hrs. occupants (4)	: 20
equipment	: 10
23-07 hrs. occupants (4)	: 20
equipment	: 5.0

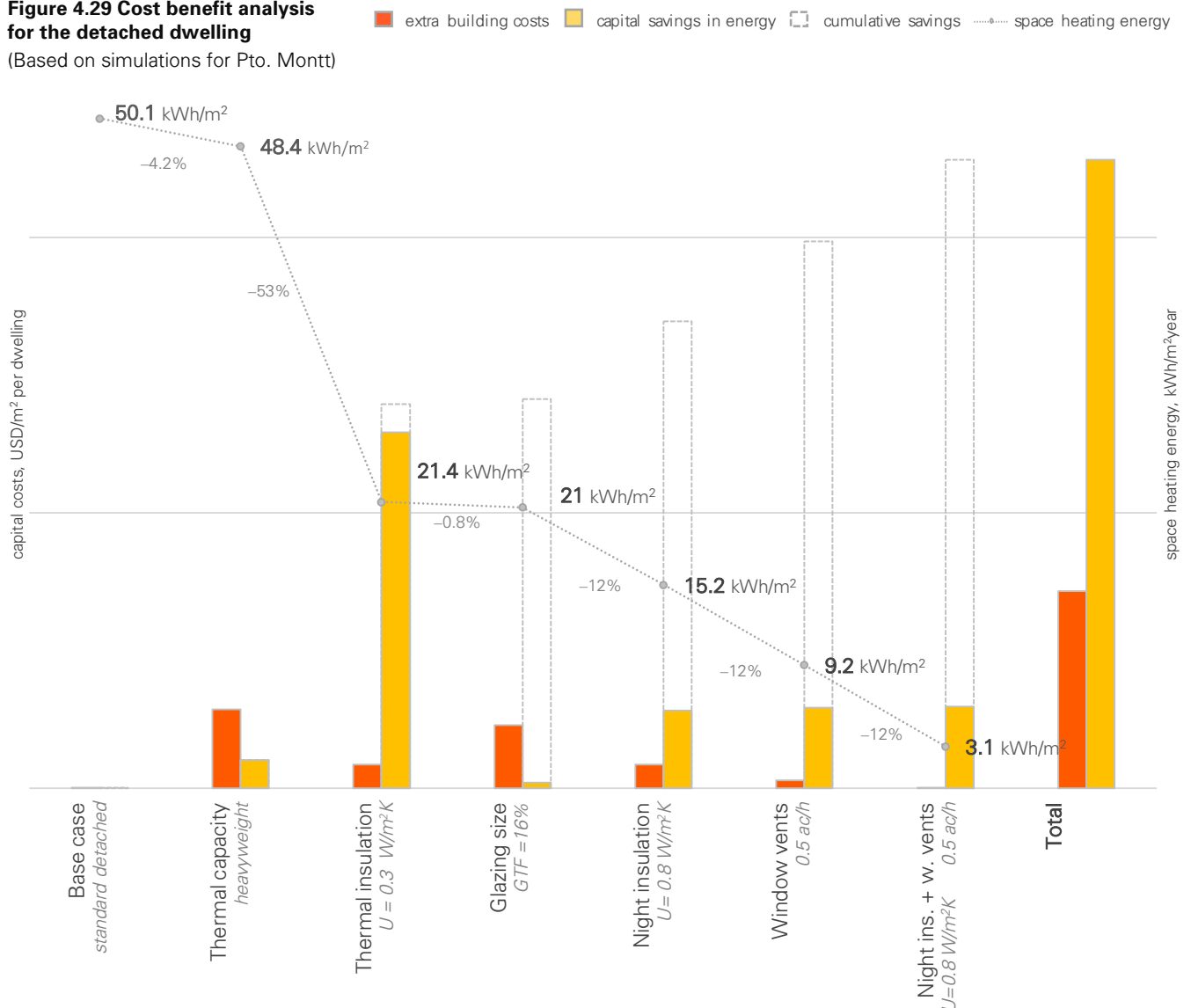
- living area
- main bedroom
- ... outdoor temperature
- daily comfort range (after de Dear 2010)
- ... global solar radiation
- solar gain living area
- solar gain bedroom



The graphs plotted from Figure 8.12 to 8.13 (Appendix 8.5), show simulation results for design variations applied to the standard base-case detached house for Puerto Montt. As shown in Figure 8.12.1, the heavyweight structure using brick masonry instead of standard timber frame constructions limited diurnal temperature ranges to 10–13°C and contributed saving only 5%. In contrast, the effect of additional wall insulation was more beneficial with the energy demand of the base case decreased by half to 25 kWh/m² year (see step-by-step reductions in space-heating energy in Figure 4.29). Thus the minimisation of building envelope heat losses, by also reducing the size of glazing, improving shutters, ventilation and airtightness was the most important measure to achieve daily winter comfort temperatures and reduce space-heating energy demand to 3.1 kWh/m² year.

Figure 4.29 Cost benefit analysis for the detached dwelling

(Based on simulations for Pto. Montt)



The variations studied for the intermediate-floor apartment of Puerto Montt showed that improved thermal comfort conditions can be achieved for multi-story buildings with less additional capital and building costs. The techniques applied to improve the performance of the apartment were more effective than those for the detached house. With less additional insulation and

glazing areas, the use of window shutters and vents contributed to raise daily winter room temperatures by as much as 5K (Figure 8.13.4), as well as reducing annual space heating demand to 1.0 kWh/m² year. Over the summer, the results of simulations showed that for both dwelling types thermal conditions can be kept by simply opening windows (Figure 8.13.5). The extra capital investment of improving standard dwellings starts at the highest at 40USD/m² per unit, with savings in space heating energy costs in the order of 800 USD per annum —these figures mean that cost-benefit ratios above 3.0 are achievable for improving any dwelling type (see Figure 5.5, in Chapter 5).

As well as offering large running cost savings in space heating energy, the benefits of applying the proposed techniques were also significant in terms of reduced combustion emissions. The energy savings achieved start at around 50 kWh/m² year translates into monthly capital amounts as large as 60% of the median poorest income quintile (CASEN, 2013), and over ninety percent less combustion emissions from using a conventional firewood heater, the equivalent of 50 kg/m² in carbon-dioxide, and 80 mg/m² in air contaminants including PM_{2.5}, CO, NO₂ and SO₂ (see emission factors in Appendix 8.4). This last foreseeable outcome is of paramount relevance for setting low emission targets to build new dwellings in southern cities, several of them currently ranked among the most polluted nationally and worldwide due to emissions from residential firewood burning (MMA, 2014; WHO, 2016).

4.5.2 Summary of Parametric Variations

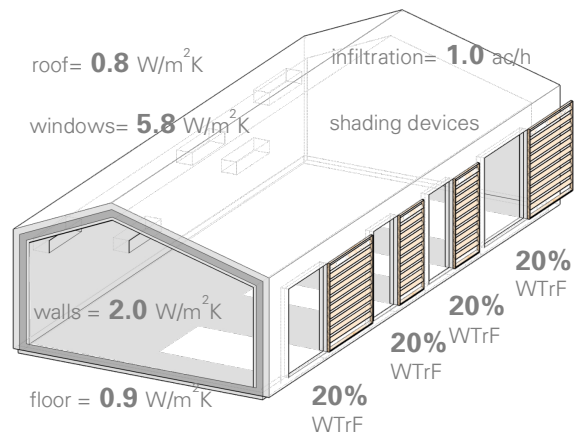
Figure 4.30 illustrates a sample of parametric models proposed for designing naturally conditioned dwellings for north, central and south regions. Specifications and alternative options for adapting these designs to meet the target performance requirements for different locations are listed in Table 4.2. The alternative options described in the table can be used to compensate for any unfavourable weather and/or site conditions as well opting for more economic construction materials when possible and when required by stakeholders. For example, in coastal locations with small outdoor diurnal temperature ranges standard lightweight timber-frame constructions can be applied by keeping window-to-floor ratios at minimum. All other design modifications to achieve occupant thermal comfort conditions were set to accord with regional variations in indoor-outdoor temperature differences.

The heat loss coefficients of the improved dwellings can be used to derive specific building envelope characteristics for different locations. As shown in Figure 4.30, based on the results of computational simulations, the heat loss coefficients of the improved dwelling designs for Santiago, Antofagasta and Puerto Montt are in the 2.0–5.9 W/Km² range, including dwellings and apartments. By performing simple calculations of mean indoor temperatures it is possible to estimate that for the coolest location (Punta Arenas), further improvements are required to meet a heat loss coefficient of 1.4 W/Km², whereas for the warmest one (Calama), a coefficient of 7.1 W/Km² will be needed to prevent excess daytime overheating. As an indication of variations in building envelope design, compared to the same dwelling for Punta Arenas described below, the detached house of Calama located in the

Northern Chile

Antofagasta (23°S)

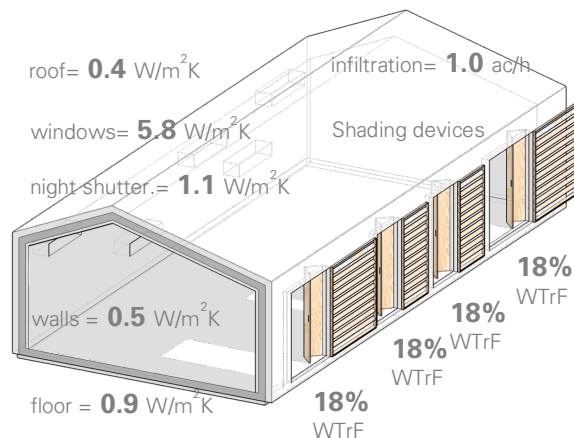
HLC= **5.9** W/Km²



Central Chile

Santiago (33°S)

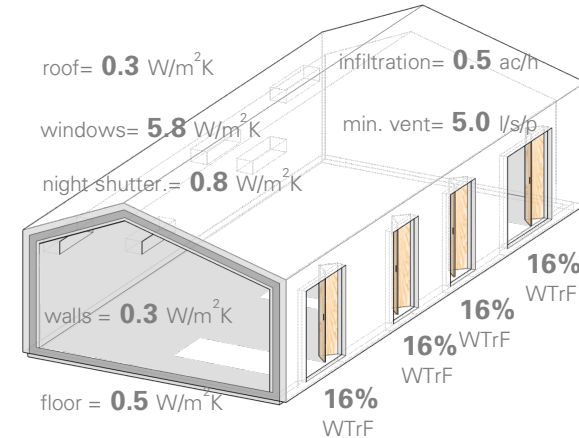
HLC= **3.9** W/Km²



Southern Chile

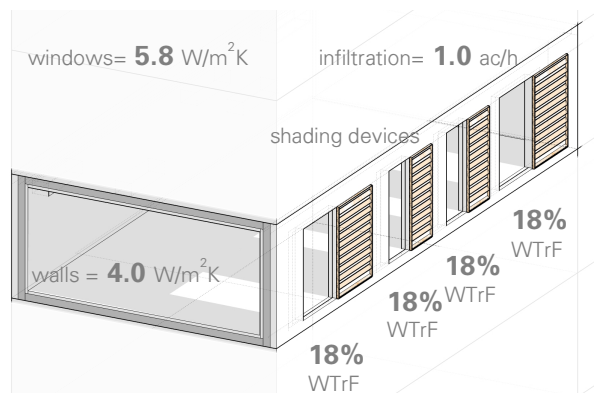
Puerto Montt (41°S)

HLC= **2.6** W/Km²

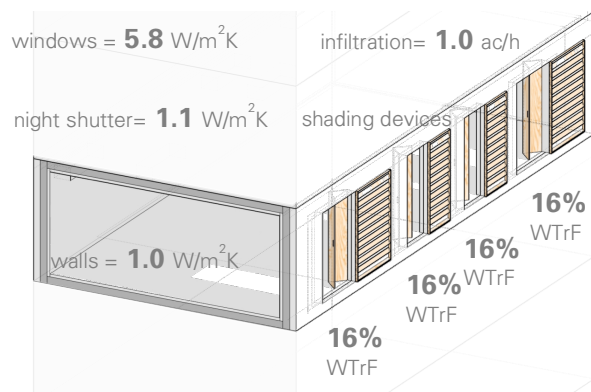


Detached houses

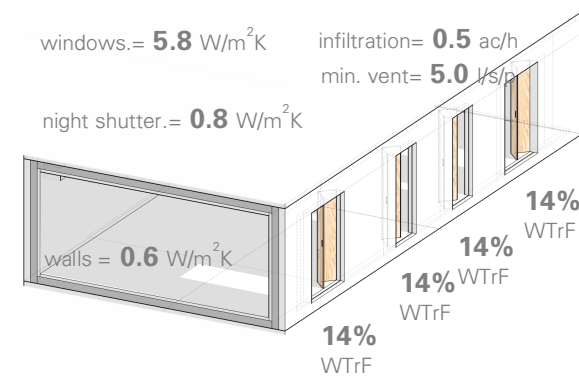
HLC= **4.4** W/Km²



HLC= **2.6** W/Km²



HLC= **2.0** W/Km²



Apartment flats

Figure 4.30 Regional design variations for naturally conditioned dwellings

The graph is based on fixed window orientations (distribution: 20% south and 80% north), brick masonry construction and heavyweight finishes, and variable adaptive comfort temperatures by location. Specifications given here can be used to derive building properties for other locations (see detailed specifications for each parametric variation from Figure 4.1 to 4.4)

Table 4.2 Summary of regional design recommendations and alternative options

	Design Guidelines	Regional Variations	Alternative Options
1.Dwelling type	<ul style="list-style-type: none"> aim for a compact building form that allows heat dissipation and air movement through all internal rooms orient and arrange rooms as a function of solar access and predominant wind 	<ul style="list-style-type: none"> in northern regions, prefer rectangular forms with relative large surface-to-volume ratios and consider fixed external shading elements in central and southern regions, prefer grouping dwellings into apartments for reducing excess envelope heat losses 	<ul style="list-style-type: none"> where an optimal building form cannot be adopted see: option 8.1 to compensate for overheating in intermediate rooms; and 3.1 for excess envelope heat losses
2.Thermal capacity	<ul style="list-style-type: none"> use heavyweight building materials to provide additional heat storage capacity specify thick exposed plaster finishes in habitable rooms (0.7 solar absorptance) 	<ul style="list-style-type: none"> in coastal locations, lightweight constructions are feasible by keeping windows at minimum admissible size 	<ul style="list-style-type: none"> (option 2.1): additional heat storage capacity: such as larger glazing areas than required (Figure 4.30), consider use of phase-change materials on internal finishes
3.Thermal insulation	<ul style="list-style-type: none"> consider insulation above minimum requirements for external walls (see indicative values by location in Figure 4.30) ensure continuity and integrity of insulation 	<ul style="list-style-type: none"> in most exposed dwelling types consider high-density insulation on the exterior to the south of Puerto Montt use ground floor insulation on exposed floor elements 	<ul style="list-style-type: none"> (option 3.1): larger heat losses than required (Figure 4.30), consider additional envelope insulation on roof and/or walls
4.Window size and type	<ul style="list-style-type: none"> adjust size of windows accordingly (see indicative values by location in Figure 4.30) orient and place windows according to room functions minimise areas of unfavorably oriented windows in service areas 	<ul style="list-style-type: none"> from central regions to the south single-glazing windows with no night curtains should be kept at minimum size keep minimum admissible glazing size for locations to the south of Puerto Montt 	<ul style="list-style-type: none"> lack of choice of orientation: consider reducing glazing size, double-glazing, and/or additional trade-off (options 6.1, 6.2 and 7.1) (option 4.1) stringent comfort provisions: consider design and integration of conservatories
5.Night insulation	<ul style="list-style-type: none"> install insulated shutters on the inside of window openings 	<ul style="list-style-type: none"> consider translucent insulation for use over evening and dusk hours 	<ul style="list-style-type: none"> consider increasing the thickness of insulation for cooler regions
6.Window vents	<ul style="list-style-type: none"> provide controllable means of ventilation consider air infiltration rates as part of the ventilation strategy 	<ul style="list-style-type: none"> (option 6.1) from south of Puerto Montt consider envelope airtightness of 0.5 ach or below 	<ul style="list-style-type: none"> (option 6.2) consider heat recovery ventilation with individual room ventilators for economy
7.Exterior shading	<ul style="list-style-type: none"> specify operable shading and avoid fixed overhangs 	<ul style="list-style-type: none"> use lightweight materials with clear or white color 	<ul style="list-style-type: none"> east-west facing windows (option 7.1): consider use of shading for different slat positions
8.Window opening	<ul style="list-style-type: none"> provide openable windows for summer ventilation place and design apertures as a function of predominant wind speed and direction 	<ul style="list-style-type: none"> (option 8.1) northern and central interior regions provide ceiling fans and/or ventilators with extracts for peak-season hot daytime hours 	<ul style="list-style-type: none"> placement of windows and vents stack cross ventilation through careful placement of openings and internal planning

Note: design variations with respect to the improved base-case for each location (Figure 4.30)

north interior should consider heavyweight constructions, less wall insulation ($2.6 \text{ W/m}^2\text{K}$) more glazing to-floor areas (25%), and window aperture size as well as use of exterior shading devices (see summary recommendations in Table 4.2).

For locations to the south of Puerto Montt special considerations should be given to minimise additional heat losses from glazing and improving envelope airtightness. For Punta Arenas, besides increasing insulation on external walls ($0.25 \text{ W/m}^2\text{K}$) and ground floor elements ($0.25 \text{ W/m}^2\text{K}$) windows should be kept at minimum size and double-glazing ($0.3 \text{ W/m}^2\text{K}$) to prevent excess daytime heat losses and additional space-heating energy—for further improvements in performance consider integration of an attached conservatory. From Puerto Montt to the south reducing envelope infiltration and ventilation becomes increasingly important in relative terms for which for Punta Arenas an airtightness of 0.3 ac/h and ventilation with heat recovery (85%) are considered (Figure 4.31). The energy indices tabulated in **Table 4.3** and **Figure 4.31** can be used to minimise the amount of analytical work required to design housing projects of any scale and grouping type across the country.

4.5.4 Savings in Space-Heating Energy

Figure 4.31 shows regional variations in space-heating energy use for the improved standard dwellings by applying the proposed design techniques to eight different locations (see selection criteria in Section 3.2). The proportion of energy saved relative to the total amount of energy use predicted for the standard base case dwellings was found larger than expected with values ranging as high as 88–98% for all locations. Residual space heating energy resulted in the order of $0.3\text{--}12 \text{ kWh/m}^2$ for the improved detached houses and below 5 kWh/m^2 for the improved apartments—as shown in Figure 4.31 space heating energy tends to vary around three to four times in value every ten-degree difference in latitude along the north-south axis of the country. The low energy levels achieved through following the design measures discussed in this study will reduce all energy use in typical households in the order of 12–82% from the northernmost to the southernmost location and thus will significantly contribute to increase the potential for completely converting domestic energy supply to renewable sources (see design of low carbon dwelling prototypes in the next chapter).

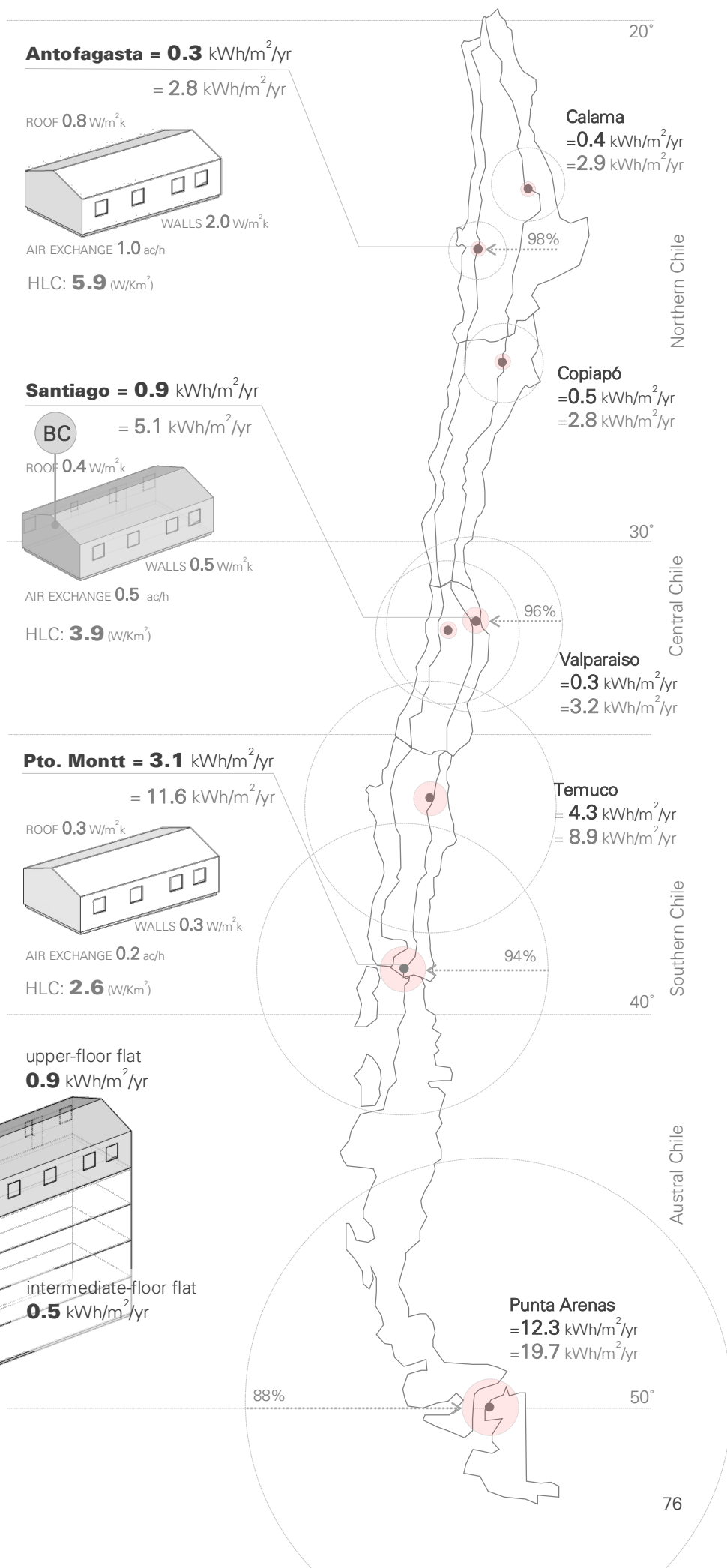
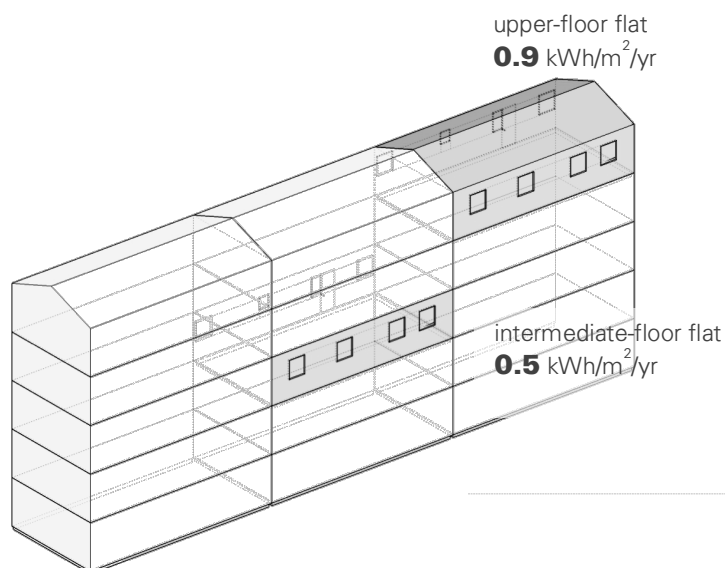
Remarkably, even for more stringent room temperature standards than those adopted for this study, the capital costs of conventional energy for space heating and cooling are within an affordable range for households of all income types. Space heating demands of $3\text{--}10 \text{ kWh/m}^2$ achieved for the apartment based on a continuous 20°C set point represent savings in the order of 90–96% compared to the base case detached dwelling using the same settings. On the other hand, in the case of households in which cooling appliances are operated at 26°C set-point the demand for energy does not exceed the $3\text{--}5 \text{ kWh/m}^2 \text{ year}$ —the base case demand for the standard apartment range above $30 \text{ kWh/m}^2 \text{ year}$ on all locations. These energy indices are proofs of the very good performance of the intermediate apartment flat and when

Figure 4.31 Regional variations in space-heating energy for improved dwellings

Space-heating energy is estimated for improved detached dwellings of 70 m² (compared to base-case assumptions), considering masonry construction and heavyweight finishes for a fixed orientation. Envelope insulation, room glazing size, window operable elements, ventilation and airtightness vary by location (for each 1.0 ac/h increase in air infiltration space-heating energy will increase by 25% in Antofagasta, by 60% in Santiago and over 80% from Puerto Montt to the south (see results of simulations in Appendix 8.5) **4.31a** (bold figures) Energy is estimated for the living area and bedrooms for a 16-hours set point of 17°C from May to September (the broken line circles are the energy estimated for the base-case assumption **4.31b** (grey figures) Energy is estimated for a whole-house 24-hours set point of 20°C with night-time setback of 17°C from April to September (see inputs for simulations in Appendix 8.5).

4.31c Space-heating energy for standard apartment dwellings

The same plan area and specifications of the improved detached dwelling is applied to different flat types in multi-storey apartment buildings (based on results of simulations for *Santiago*).



translated into monthly capital amounts they represent less than 5% and 3% of the median poorest household income quintile (CASEN, 2013), respectively, for space heating and cooling end uses.

A summary of regional variations in space heating energy for each design parameter is given in **Table 4.3**. The table gives a comparative measure of the cumulative effect of the different design techniques applied to the detached house and the intermediate-floor apartment (see also regional variations in extra capital costs in Section 6.2). The table also highlights regional differences in space-heating energy as a function of dwelling type, showing that along the country the improved apartment needs around half the amount of energy required for the detached house. By considering these results and previous analytical work performed in previous chapters, it can be observed that while among the benefits of opting to build apartments are their better performance as well as lower initial and extra capital costs, the high embodied energy and carbon emissions associated to their construction are still major drawbacks compared to traditional low density housing.

Table 4.3 Effect of design variations on space heating energy (kWh/m² year)

<i>Building design variation</i>	<i>Antofagasta</i>		<i>Santiago</i>		<i>Puerto Montt</i>	
	<i>detached</i>	<i>apartment</i>	<i>detached</i>	<i>apartment</i>	<i>detached</i>	<i>apartment</i>
Base-case dwelling	12 – 8		25 – 18		50 – 36	
heat loss coefficient, W/Km ²	7.7 – 5.6		5.1 – 3.9		2.0 – 2.6	
Thermal capacity	10 – 7		15 – 13		46 – 33	
solid brick masonry construction						
Thermal insulation	4 – 3		6 – 6		21 – 20	
wall thermal transmittance, W/m ² K	2.0 – 4.0		0.5 – 1.0		0.3 – 0.6	
Window size	0.3 – 0.2		5 – 4		21 – 16	
room glazing-to-floor ratio, %	20 – 18		18 – 16		16 – 14	
Insulated shutter	-	-	1.9 – 1.3		13 – 9	
thermal transmittance, W/m ² K			1.1 – 1.1		0.8 – 0.8	
window vents	-	-	0.9 – 0.5		8 – 5	
ac/h per person	1.0	1.0	0.5 – 0.5		0.5 – 0.5	
airtightness	0.3 – 0.2		0.9 – 0.5		3.1 – 1.5	
ac/h	1.0 – 1.0		1.0 – 1.0		0.5 – 0.5	
Improved dwelling	0.3 – 0.2		0.9 – 0.5		3.1 – 1.5	
Heat loss coefficient, W/Km ²	5.9 – 4.4		3.9 – 2.6		2.6 – 2.0	

Note:

4.6 Conclusion

The results of simulations performed for this chapter have proven that there is a wide range of design options for which occupant thermal comfort conditions can be achieved passively in new standard dwellings. Through including a range of different dwelling types and building materials the results of simulations showed that differences in outdoor climate conditions across the main inhabited region of the country can be offset economically by adjusting statutory insulation and glazing size and specifying better building controls (blinds, shutters and vents). A graphical explanation of the design principles and choices available for application of the strategies proposed in this study is provided through a demonstration project presented in the following chapter.

5 Delivering Low-Carbon Prototypes

5.1 Introduction

This chapter demonstrates the applicability of the research through proposing low-energy dwelling prototypes that can be used to build multi-unit residential developments. Specifications derived from the results of thermal simulations performed in previous chapters are developed into a low-carbon modular prefabricated construction system that uses suitable building materials for delivering naturally conditioned dwellings nationwide. The construction strategy considers specification of locally sourced building materials as well as integration of distributed renewable energy sources for reducing conventional energy use and carbon emissions at different stages of housing development.

5.2 Construction System

A demonstration project to apply the design techniques proposed in this study was performed by following guidelines and specifications drawn from the preceding chapter. As explained earlier throughout the thesis the methodology for design of naturally conditioned dwellings consists firstly of choosing a suitable dwelling type and building materials, and secondly, applying design guidelines and specifications derived from the results of parametric simulations in Chapter 4 (see summary specifications for detailing in Figure 4.30). By careful application of the techniques designed for minimising conventional space-heating and cooling energy the example project presented in the following paragraphs also aims at assessing the potential for reducing lifecycle carbon dioxide emissions and residual domestic energy uses in housing.

The design objective is to propose a highly adaptable modular construction system for mass prefabrication of low-carbon residential prototypes. The construction and joinery system planned for integrated digital design delivery was developed for building mid and high-rise multi-unit housing developments (see range of dwelling types in Figure 5.5), as well as being adapted and replicated to minimise conventional space heating and cooling energy at any given location across the country. The project is addressed for households of low to middle income quintiles (see target household groups in Section 3.2) who can afford dwellings whose construction costs and finishes are no more than 400 USD/m² (see building cost of different options in Table 5.2). Chosen from the range of building materials selected in this study (Figure 3.9), the constructions used for implementation of the project were selected to balance affordability with optimal thermal, energy and environmental performance.

Figure 5.1 Construction process for delivering low-carbon dwelling prototypes using timber

Modular panels and utility modules are manufactured off-site (1), shipped (2), assembled on designated locations (3) and erected into the building configuration structure of choice (4). The panelised system can be dismantled and reused to build other projects (5), or as material for furnituring, housebuilding, or as biomass fuel.

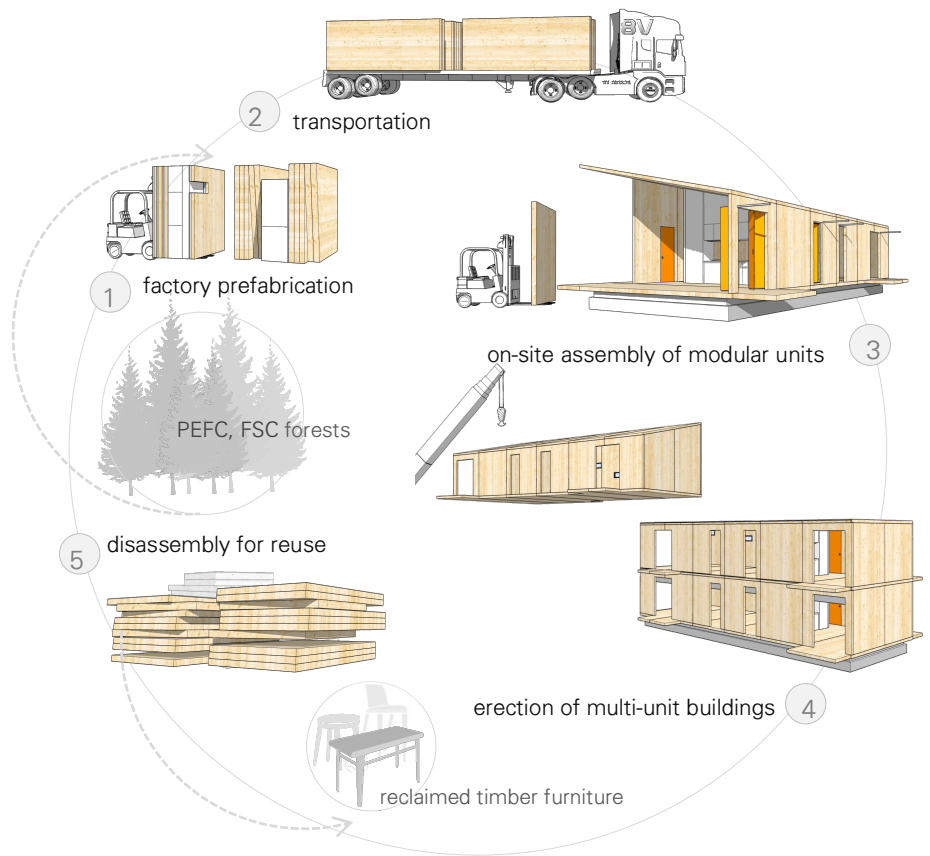
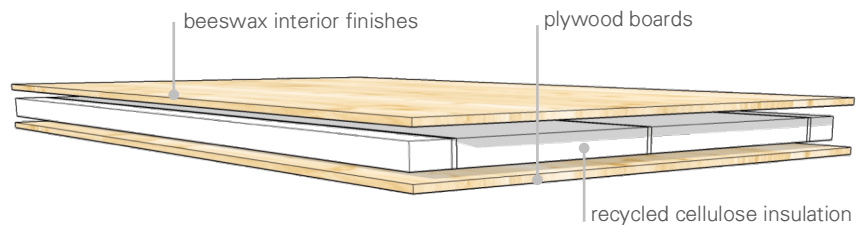


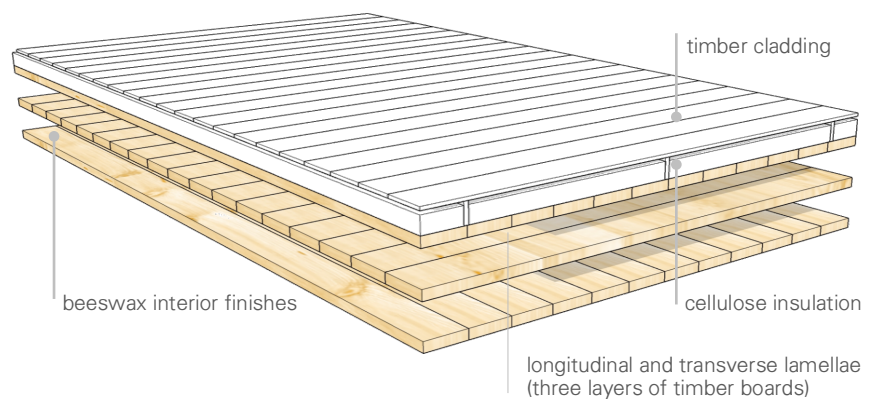
Figure 5.1a Specification of prefabricated timber elements and panels

The construction strategy aims to maximise the use of locally available building products. The CLT panels specified for the prototype are manufactured by bonding typical *insigne pine* studs using structural adhesives and wood dowels for reinforcement (CI-TEC UBB, 2014). Prefabricated plywood SIP panels are sourced from local market suppliers at 24 USD/m² (see cost estimation in Appendix 8.3).

structural insulated panel (SIP)



cross-laminated timber (CLT) panel



5.2.1 Building Materials

The strategy for delivering low-carbon prototypes is to design a high performance building envelope system using modular prefabricated timber panels (**Figure 5.1**). The results of the analytical work performed in previous chapters confirmed that with less additional capital costs apartment accommodations can achieve better energy and thermal performance than standard low density housing. However, while it was argued that conventional apartments built on reinforced concrete are more energy-intensive than timber-frame houses both construction types have important limitations to meet current demands for affordable low-carbon housing (BRE & MINVU, 2015). The use of locally-sourced timber materials to build multi-unit residential buildings is an opportunity for developing in Chile a more environmentally and socially responsive affordable housing model.

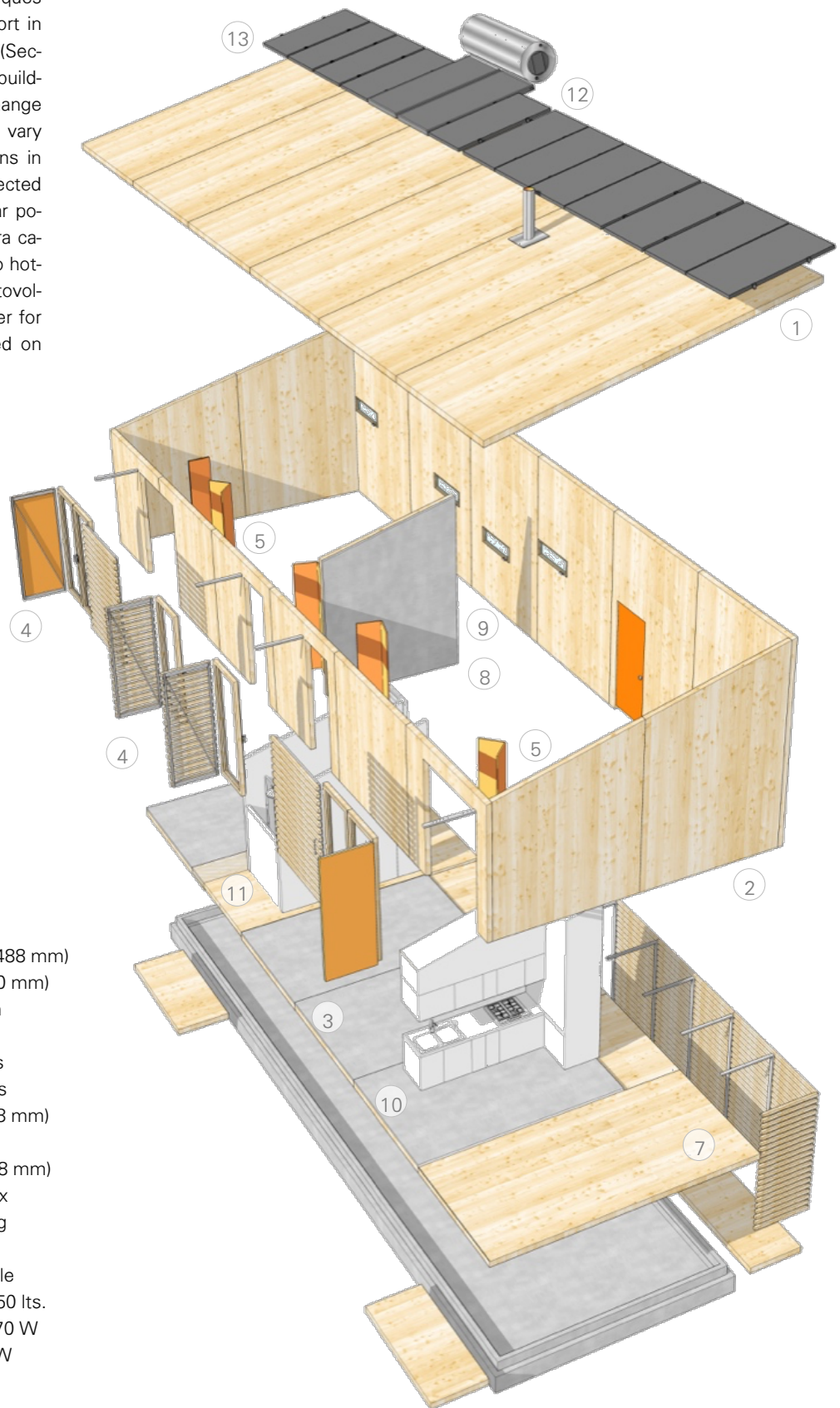
The construction of multi-unit residential developments using responsibly sourced timber materials has many undervalued technical and environmental advantages for wide application nationally (**Figure 5.1a**). First, Chile is among the largest producers of manufactured timber worldwide (INFOR, 2015) and therefore has the resources to manufacture highly engineered timber products for mass prefabrication of large residential buildings (FONDEF, 2001; Pascha, 2012). Second, timber materials from certified sustainable forests (e.g. PEFC, FSC) have low embodied energy and their use in construction is considered carbon-negative meaning they absorb more carbon dioxide during the growing of trees than they release over their manufacturing process (CORMA, 2015). Third, compared to conventional constructions, prefabricated timber panels can be made cheaply and more thermally efficient for delivering naturally conditioned dwellings to almost any region in Chile (see assessment of building materials in Section 3.3). Fourth, prefabricated timber dwellings can be delivered to highly dense urban and remote rural site locations allowing quick erection, use of local labor and material resources.

Among the limitations of using prefabricated timber materials for building low-carbon dwellings are their low heat-storage capacity and high current manufacturing capital costs. These disadvantages were addressed in this research project by combining the use of cross-laminated timber (CLT) and high density cellulose insulation and plaster finishes which have the additional level of thermal mass required for the building envelope and the use of structural insulated panels (SIP), currently among the cheapest prefabricated options available in the market (**Figure 5.1a**). The following list drawn from recently published research reviews the most relevant technical and environmental advantages considered in this research project for using prefabricated timber panel systems (FONDEF, 2001; Perez et al., 2010; Weihephan, 2011; Lehmann, 2013; Cambiaso & Pietrasanta, 2014; CLTChile, 2015):

- manufactured timber materials can be sourced countrywide
- timber constructions have at least 50% less embodied energy and 25% CO₂ emissions than conventional brick-masonry and concrete
- each cubic meter of timber from responsibly grown forests sequesters approximately one tone of CO₂ from the atmosphere

Figure 5.2 Deployable prototype unit: passive design features

The specifications depicted below are based on passive design techniques applied to achieve thermal comfort in naturally conditioned dwellings (Sections 4.3 and 4.4). Window size, building envelope insulation, air-exchange rates and element specifications vary by location (see regional variations in Table 5.2). The prototype is projected to be equipped with electric solar powered equipment and for an extra capital of 130 USD/m² including two hot-water collectors, 12 (250W) photovoltaic panels, and an on-grid inverter for backup energy and supply (based on estimations for Santiago).



Exploded modular unit

1. CLT ceiling panels (90 x 244 x 488 mm)
2. CLT wall panels (90 x 244 x 230 mm)
3. heavyweight plaster floor finish
4. practicable shading screens
5. foldable vinyl insulated shutters
6. window-frame and ceiling vents
7. CLT slab panels (90 x 244 x 488 mm) (altered if unit attached below)
8. SIP interior partitions (244 x 488 mm)
9. plaster wall finish with beeswax
10. exterior plastic-timber cladding
11. prefabricated kitchen module
12. prefabricated bathroom module
13. hot-water panels, 2 units of 150 lts.
14. solar PV panels, 12 units of 270 W with on-grid inverter of 3,000 W

- timber materials are at least a quarter lighter than conventional heavy-weight counterparts allowing reductions in foundation size and costs
- dwellings built on CLT panels reduce extra building capital and running energy costs required for occupant space-heating and cooling
- CLT and SIP panel systems can be easily designed for achieving airtightness and minimising thermal bridging through building envelope
- as well as having distinct natural aesthetic qualities, interior wood finishes contribute to stabilise diurnal temperature ranges and humidity levels as well as improving sound deadening
- prefabricated dwellings built on CLT and SIP panels can be erected at least 30% faster than conventional brick-masonry and concrete
- prefabricated timber panel structures can be built and dismantled on-site causing little noise, air pollution and solid waste

The construction system adopted for this research project was designed for expediting and reducing the capital and environmental costs of delivering low-carbon prefabricated timber prototypes. As shown in **Figure 5.1**, there are three distinct stages in the construction process: prefabrication, assembly and disassembly of dwellings. During the prefabrication stage, timber panels are pre-dimensioned, cut and finished with insulation and cladding, under controlled factory conditions prior to transportation. Modular dwelling units can then be rapidly assembled on-site relying on low-skilled labor, simple fitting tools and lifting machinery to stack units together into single multi-unit building structures. After useful life, building panels and components can be easily removed, recycled or reused for other purposes. The construction system can be digitally fabricated using a modular deployable unit whose design can be adjusted to achieve high thermal comfort standards for a variety of climate conditions, different housing configurations and scales.

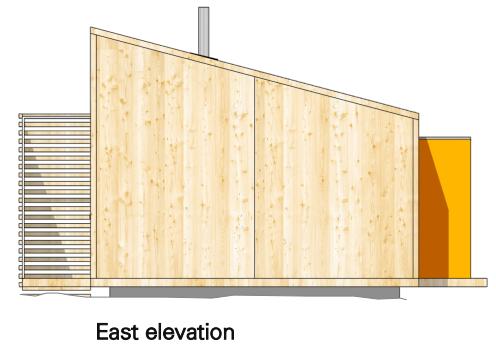
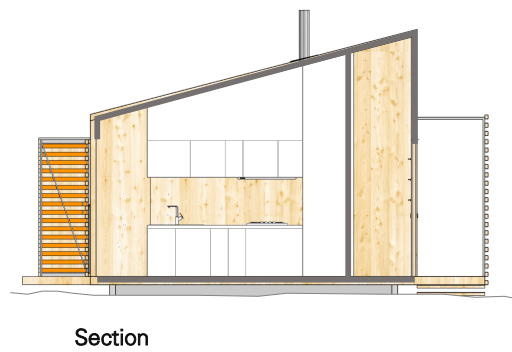
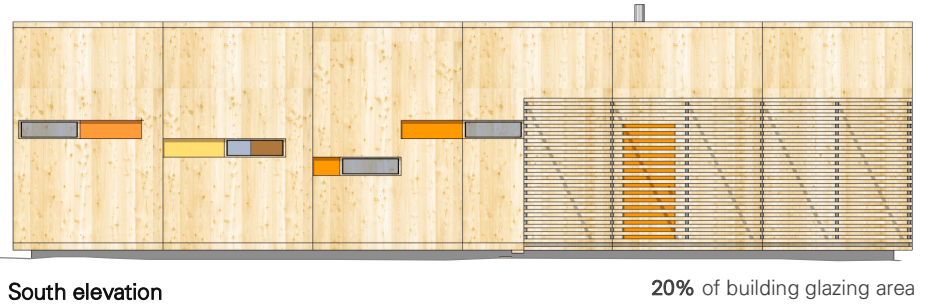
5.3 Modular Prefabricated Prototype

The design of the modular dwelling unit draws upon the passive strategies and techniques developed in this research project to propose a flexible and customisable low-carbon construction system. The prototype shown in **Figure 5.2** is a single-family house of 70m² modularized into prefabricated timber panels that can be arranged in different ways to form either one or two storey dwellings, multi-unit housing or apartment developments (see prototyping options in Figure 5.5). The technical specifications of the modular prototype comply with national regulations and standards applying to dwellings built under the HSFP (see plan and specifications in **Figures 5.3** and **Figure 5.4**). The design of the prototype which has an open-plan space with a high performance building envelope shell can be customised by stakeholders who can arrange panels to create different spatial layouts and/or develop progressive growth strategies (see detailing for mountable panels in Figure 5.4).

Table 5.1 shows regional variations in design specifications for the modular dwelling unit based on results of simulations for Santiago, Antofagasta, Puerto Montt and Punta Arenas (see design guidelines in Figure 4.30 and Ta-

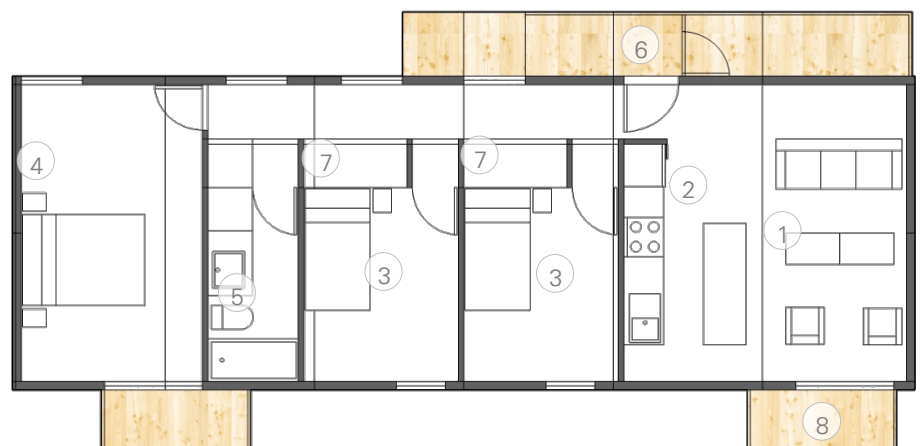
Figure 5.3 Deployable prototype unit: plan, section and elevations

The building design and specification of operable envelope elements are based on results of parametric simulations for Santiago (see Section 4.3 and 4.4). Room height, floor area and window requirements for daylighting and ventilation comply with technical specifications applying to dwellings built under the HSFP (2017).



Floor plan

1. living area (21 m²)
2. Kitchen module (8 m²)
3. bedrooms (9 m²)
4. main bedroom (12 m²)
5. bathroom module (8 m²)
6. corridor closet and bookshelf
7. exterior balconies (optional)
8. exterior loggia
9. main entrance



ble 4.2). As depicted in the table below, when required by specifications, additional thermal capacity can be provided by using high-density cellulose insulation and plaster finishes on internal room surfaces and utility modules (see also Figure 5.2). Remarkably, by using the proposed envelope panel system no additional thermal insulation is required for achieving indoor comfort temperatures for any dwelling type in northern regions and for apartments in central regions. For extreme south locations, besides reducing glazing size and specifying double glazing, stringent airtightness measures can be achieved economically by careful specification of air-sealing tapes and gaskets in structural joints and envelope openings (Figure 5.4).

Table 5.1 Regional design specifications for the modular prototype

<i>Design specification</i>	<i>Antofagasta</i>	<i>Santiago</i>	<i>Puerto Montt</i>
thickness of exterior panels (mm)	70	90	90
additional roof insulation (mm)	3	50	80
design requirement (W/m ² K)	0.8	0.4	0.3
additional wall insulation (mm)	-	30	80
design requirement (W/m ² K)	2.0	0.5	0.3
room window-to-floor area (%)	20	18	16
interior insulated shutter (W/m ² K)	-	1.1	0.8
envelope airtightness (m ³ /hm ²)	≥2.6	≤2.6	≤1.3

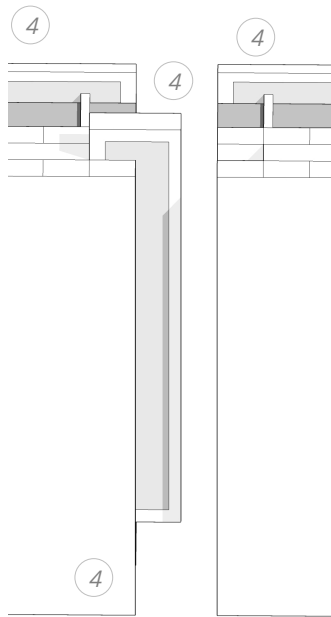
Note: based on results of simulations for the base-case, see specifications by location in Figure 4.30

A number of components and elements of the building envelope system were designed to be user-responsive in order to allow individual control of space temperatures. Occupant thermal comfort conditions were improved by specifying operable envelope components whose effectiveness on improving room temperatures were tested through extensive simulation analysis (see results in Sections 4.3 and 4.4). These components are lightweight softwood and vinyl devices, namely foldable internal insulated shutters, window-frame vents and exterior shading screens integrated into structural panels to form a continuous user-responsive envelope system. As shown in Figure 5.4, envelope panels are interlocked with each other using wood studs and self-drilling screws and as required by specifications finished with high-density cellulose insulation and a breathable weather proof membrane behind the wood cladding system.

To address residual energy demands for space-heating and cooling and other domestic end uses the design of the prototype also contemplates the integration of distributed solar energy technologies—including on-grid metering devices and connectors (Figure 5.3). The single-storey detached unit has more than enough roof space for installing the number of solar hot-water and photovoltaic (PV) panels required for complete supply of renewable energy to household users of northern, central and southern locations (see residual en-

Figure 5.4 Deployable prototype unit: specification of timber envelope elements

Envelope specifications are based on recommendations for design of naturally conditioned dwellings for Santiago (Section 4.3 and 4.4). Regional variations in building envelope properties and specifications can be consulted in Table 5.1. The section and details are indicative of the main issues of detailing with prefabricated CLT panel systems (After Karacabeyli & Douglas, 2013)



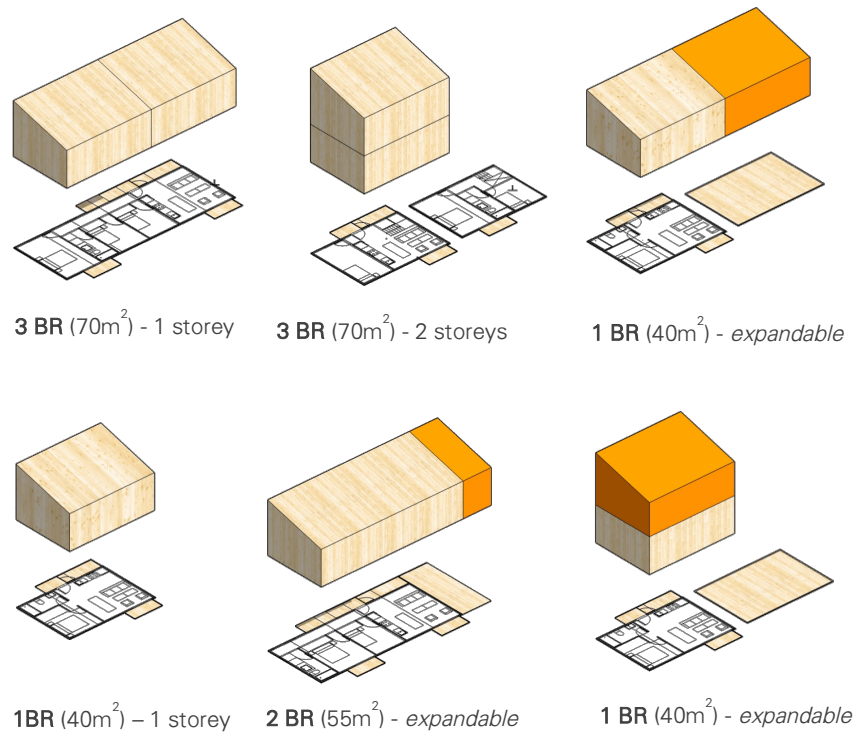
Prefabricated panels

1. structural CLT panel (90mm)
2. recycled cellulose insulation
3. plywood panels (10 mm)
4. air-sealing membrane
5. exterior timber cladding (10 mm)
6. steel bracket
7. interlocking timber strap
8. Sill plate laid in mortar bed
8. joint tape (if airtightness required)



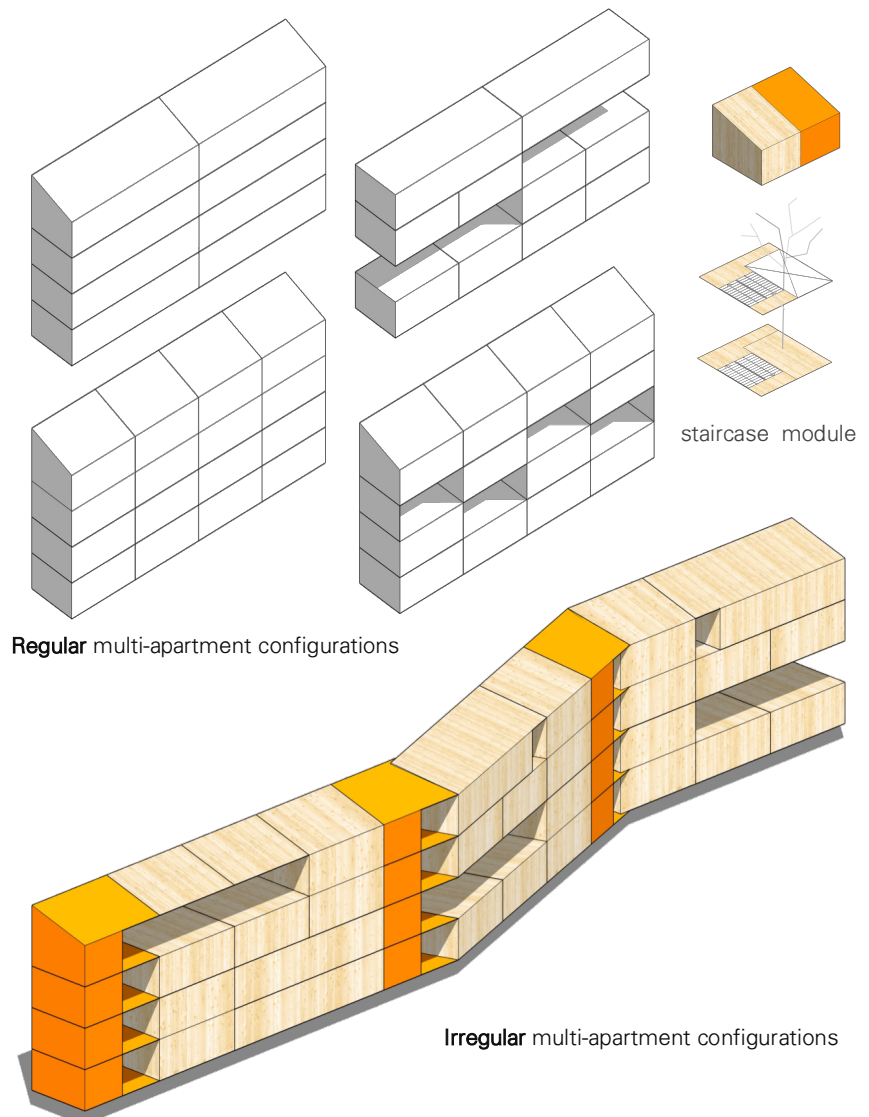
Figure 5.5 Prototyping options: dwelling types and configurations

The prototype was designed to meet new standard dwelling types: single and two storey detached houses, and flats of different room distribution and size ranging in floor area from 40m² to 70m². The modular CLT construction system allows for integrating expandable units for multi-housing buildings either through interior growth or exterior expansions on prebuilt structural CLT slabs. Future spatial changes can be easily applied by occupants using basic woodworking skills and tools to mount and dismount partition panels.



Multi-unit apartment buildings

Apartment buildings can be deployed at different scales and multi-unit configurations. A wide range of outcomes can be built either through the stacking of different fixed and expandable dwelling unit types. Apartment buildings are assembled from combinations of the same floor, wall, ceiling, kitchen, and bathroom modules. Contrary to this maximum level of prefabrication and modularity at the level of assembly, the system is intended to flex and adapt to site particularities through deformation in plan and differences in stacking height.



ergy use for reference households in Section 4.5). For instance, in the case of Santiago, the projected installed capacity of solar panels is sufficient for harvesting the energy required to supply the annual residual energy use of four reference households (see specifications in Figure 5.3).

The affordability of the prototyping system is improved by grouping individual dwelling units into multi-storey apartment buildings (see prototyping options in Figure 5.5). At lower building capital costs than standard low density housing configurations, opting for multi-unit apartments will allow providing improved occupant thermal comfort, lower running space-heating costs and polluting emissions (Section 4.5), as well as achieving economies of scale in prefabrication, construction and installation of solar district energy and other residential energy facilities. As shown in Figure 5.7, following on-site assembly of the building enclosure and utility modules, modular apartment units are lifted and stacked together using interlocking CLT wall and slab panels.

A prefabricated construction system that is easy to mount and dismount and can be used to build multi-storey timber buildings opens a wide range of innovative urban affordable housing solutions, such as: progressive growth, adaptive reuse, additions to existing infrastructure, mixed use and mixed-income developments (see example project in Figure 5.8).

5.4 Benefits in Construction and Operation

Substantial reductions in embodied energy use were achieved by specifying prefabricated timber building materials. The total capital costs estimated for the construction of the modular prototype unit was 320 USD/m², including the building structure, finishes and passive design features (see cost estimations in Appendix 8.3). With further development in the manufacturing of CLT it is expected that significant capital cost reductions can be achieved in a near future. As shown in Table 5.2, compared to standard brick-masonry and concrete dwellings the timber prototype will require 51.6% and 60% less energy for manufacturing building materials, 6 and 9 times the national annual domestic energy use per household (CNE, 2014). Further planning for optimization of the construction process will have relative meaningful effects on reducing the residual energy use of low-energy dwellings.

Table 5.2 also adds evidence that by building and operating low-energy prototypes there is great potential for reducing lifecycle carbon dioxide emissions. As shown in Table 5.2, for manufacturing building materials the modular prototype will emit 128 kgCO₂/m², 34% and 44.4% less than standard brick-masonry and concrete dwellings (see data sources and estimations in Appendix 8.4). Considering that 30m³ of timber will be required for construction approximately 428 kgCO₂/m² will be captured from the atmosphere during the growing of trees (CLT-Chile, 2015). Furthermore, over useful life, the prototype will avoid annually in the order of 10–60 kgCO₂/m² due to savings in running space-heating energy (see regional variations in space-heating energy use in Section 4.5). Lifecycle balance estimates show that by careful design and specification of building materials the construction of low-energy dwellings can be planned strategically as a systematic means to store carbon and avoid environmentally adverse combustion emissions.

For reducing residual domestic energy use through integration of distributed renewable energy technology low profitability levels were identified. The major barrier encountered was the high present capital costs of purchasing and installing solar panels which in the case of Santiago requires an additional capital investment of 130 USD/m² to meet the annual residual energy use of the reference household (Figure 5.2). Although investing on the installation of solar panels will allow large relative capital savings in running energy costs, the extra capital cost per kilowatt-hour of energy exceeds by over 40% that needed for applying passive building design techniques, the equivalent of 2.0 USD/kWh annually with a discounted payback period of 8.4 years (see summary of extra capital costs in Section 6.1).

From all of the analysis performed for the prototype it can be concluded that opting for building multi-unit apartment configurations will provide the greatest capital and environmental advantages. The summary of indices tabulated for different dwelling configurations in **Table 5.2** provides additional confirmatory evidence that compared to multi-unit detached, apartment configurations are more cost-efficient for reducing the energy consumption and carbon emissions of dwellings. Moreover, compared to traditional building constructions, the flexibility, low weight and speed of assembly of the prototype offer significant advantages for infill apartment development. Multi-storey timber apartment buildings can be projected to be built within a variety of tight inner-city locations increasing the range of choices for locating housing developments as well as improving access to public transport, community infrastructure and facilities (see example project in Figure 5.8).

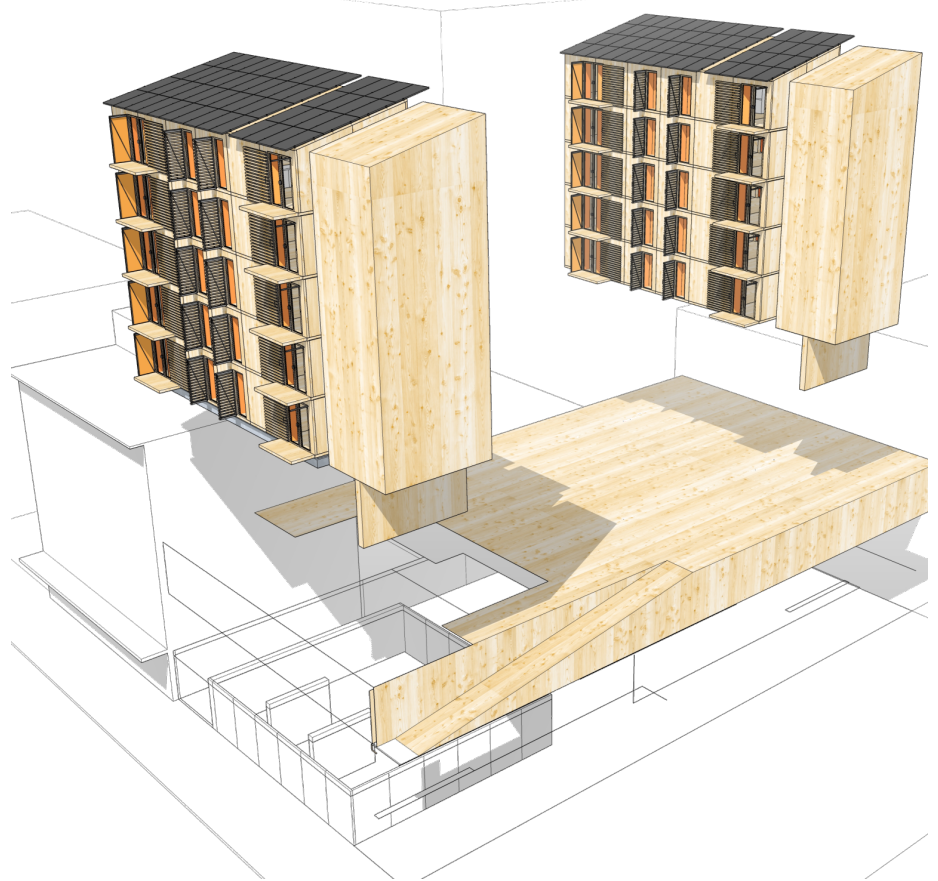
Table 5.2 Summary of building performance indices for different configurations

	Multi-unit configuration	Building construction				Space conditioning			Water heating		Electric equipment	
		embodied energy kWh/m ²	carbon emission kgCO ₂ /m ²	capital cost USD/m ²	extra-cost USD/m ²	energy demand kWh/m ²	carbon emission kgCO ₂ /m ²	energy cost USD/m ²	energy demand kWh/m ²	hot-water panels USD/m ²	energy demand kWh/m ²	electric PV panels USD/m ²
Prototype	Single-storey detached	541	128	284	36	0.9	0.24	0.15	26	42	39	88
	Multi-storey apartment	398	96	249	24	0.5	0.14	0.09	26	38	39	80
Standard	Single-storey detached	1,048	377	202	36	25	6.67	4.17	26	42	39	88
	Multi-storey apartment	771	283	160	24	15	4.05	2.51	26	38	39	80

Note: electric equipment includes electric appliances, lighting and cooking (after MINEN, 2010); solar panel costs include purchase and installation costs for 2 hot-water and 12 electric PV panels; the standard dwellings in the table are specified for brick-masonry constructions based on results of simulations for Santiago (indices are given per unit dwelling, considering 70m² floor area)

Figure 5.6 Design of low-energy infill apartment developments

The prototyping system can be used to build multi-unit apartment buildings in narrow inner-city sites where building time, quality and skilled labor are constraints. The proposal depicted in the figures is a 5-storeys mixed-use apartment development with two and three-bedroom units and an open-plan expandable units. **5.6a** view of the interior open patio at the roof deck level: common space is maximised and organised around open courtyards over the existing building structure destined for commercial and leisure use.



Apartment development

1. studio apartments (4 units)
2. one bedroom apartments (4 units)
3. two bedroom apartments (6 units)
4. three bedroom apartments (6 units)
5. bikes (storage/mech/wkshp)
6. existing commercial building



Figure 5.7 Construction of low-energy dwellings in remote rural areas

The flexibility and versatility provided by the CLT prototyping system allows an ample range of choices for delivering low-carbon and low-energy dwellings to remote rural areas and in situations needing speed construction such as disaster relief projects. **5.7a** Interior view of an apartment with CLT panels exposed on the interior **5.7b** Assembly of an apartment development for post-disaster reconstruction in south Chile.



Apartment development

1. studio apartments (10 units)
2. one bedroom apartments (10 units)
3. two bedroom apartments (40 units)
4. three bedroom apartments (4 units)
5. bikes (storage/mech/wkshp)
6. existing commercial building



6 Conclusions

6.1 Summary of Findings

Based on evidence from field studies, the present research project has led to better understanding of the nature and current extent of fuel poverty in Chile. Remarkable discrepancies were found between the predictions of space-heating energy use reported in the published literature and the actual energy use incurred by occupants maintaining acceptable indoor thermal comfort conditions. The former were found to seriously overpredict energy consumption. Moreover, improved building design to meet occupant thermal comfort preferences was seen to offer a wide range of affordable alternatives for effectively contributing to alleviate current dependence on conventional fuels.

Following study of the national dwelling stock and current building regulations, three strategic research directions were identified for improving building design to alleviate energy consumption. First, increasing the thermal insulation and heat storage capacity of the external building envelope. Second, increasing glazing areas and providing operable envelope components for occupant control of solar gains and heat losses. Third, covering the cost of the above improvements from capital cost savings resulting by grouping dwellings into multi apartment building configurations. The foreseen contribution of these design measures taken together led to proposing a national strategy for delivering naturally conditioned free-running buildings.

Simulations performed to assess the proposed design measures showed that it is possible to do away with conventional space heating and cooling energy use in most of the country. Savings in space heating energy were estimated in the range of 88–98% between the warmest (Antofagasta) and coolest (Punta Arenas) location, with respective residual energy demands of 0.5–12.0 kWh/m² for detached dwellings and below 5.0 kWh/m² for apartments, that is nearly-zero for most part of the country. In dwellings where no additional energy is being used for space heating or cooling results of simulations showed that indoor temperatures can be kept at acceptable levels all-year round in a region comprising over 85% of existing dwelling stock. The simulations also helped to identify a number of relevant additional benefits:

It was found that at low or no additional capital high profitability levels can be provided to public and private-owner developers. Extra building capital on additional design measures applied to standard detached houses resulted between 24–50 USD/m² from Antofagasta to Punta Arenas (Table 6.1), as low as 5.6–12% of the minimum housing budget allocated by the government

(HSFP, 2016). For the same conditions and number of dwellings than for detached houses no extra capital will be required for improving standard apartments in Northern, Central and Southern Chile. Due to capital savings in import and generation of fuel for space-heating *public developers* can achieve profitability levels by either opting for building apartments or improving detached houses requiring special provisions (e.g. using gas central heating), for which discounted payback periods of below 5 years can be achieved (Table 6.2). In the case of *private-owner developers* discounted payback periods due to capital savings in running space-heating energy for detached houses decrease from the warmest to the coolest location from 8 years to as little as 2.8 years with respective cost-benefit ratios at 1.4 and 4.9 after the first decade of implementation.

Large capital savings: in running space-heating energy will be provided to final household users of different income groups. Depending on fuel prices, heating schedules, and thermostat preferences, capital savings in running space-heating energy can translate into as much as over 60% of the monthly capital income of households. As shown in **Figure 6.1**, for Santiago and Punta Arenas, respective monthly capital savings in running space-heating energy costs represent more than 24–44% of the median national poorest quintile (CASEN, 2015). In households requiring stringent provisions larger resultant energy savings translate into similar ratios of over 24% but for richer income groups bringing larger capital returns and profitability levels than those for the reference household users (Table 6.1).

Improved environmental quality: as well as reducing exposure to extremes of high and low indoor temperatures and achieving occupant thermal comfort, improved dwelling designs increase average room daylighting factors by 15% and 10% in the northernmost (Antofagasta) and southernmost locations (Punta Arenas), respectively, as well as improving control of internal luminous levels with provision of operable shading devices. By also ensuring

Figure 6.1 Regional variations in household income savings from space-heating

Space-heating energy for standard base-case and improved dwellings, assuming use of electric space-heaters for a 16-hour thermostat of 17°C from May to September. Median monthly income per household quintile (from CASEN, 2013); price of electricity (after Chilectra, 2015).

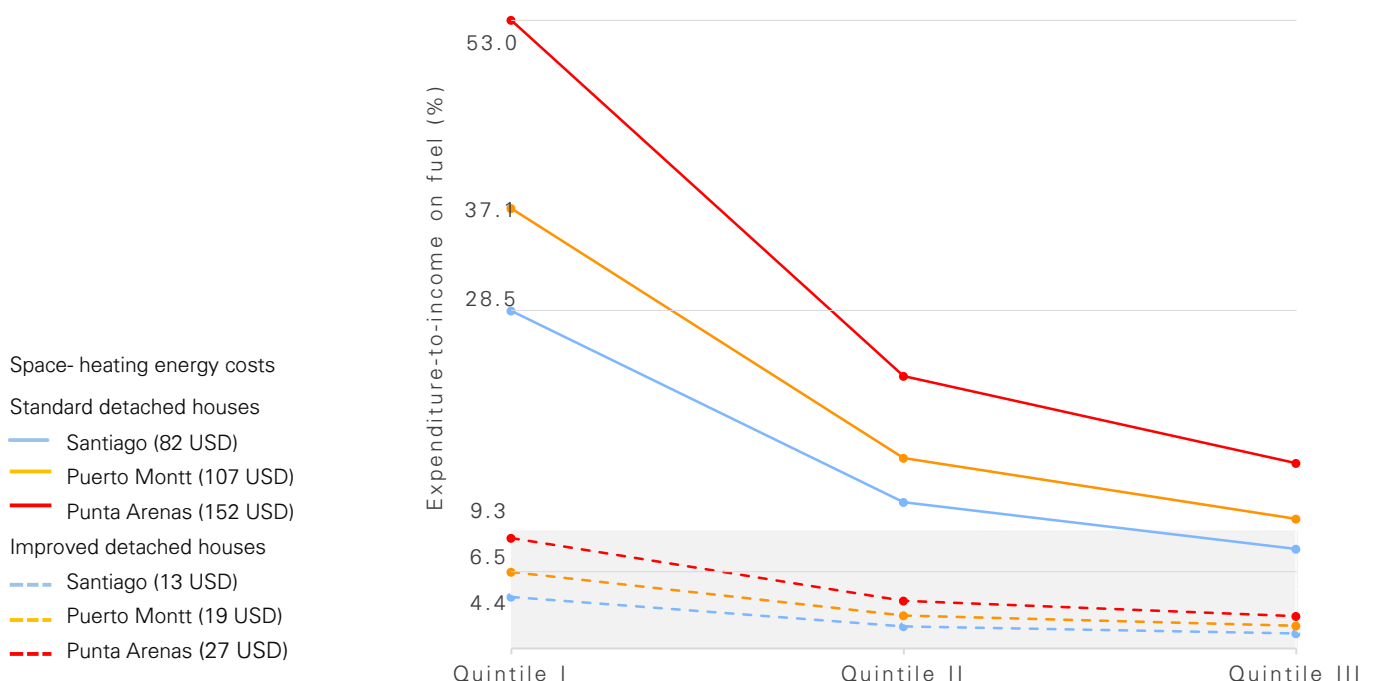


Table 6.1 Regional variations in energy and capital costs (detached dwelling)

	<i>Antofagasta</i>	<i>Santiago</i>	<i>Puerto Montt</i>	<i>Punta Arenas</i>
Extra-capital costs USD/m ²	24	36	40	50
Energy savings kWh/m ² year	11.7	25.7	46.9	86
Extra-capital costs per saved energy kWh/m ² year	2.1	1.4	0.9	0.6
Cost-benefit ratio 10 years	1.4	2.0	3.7	4.9
Cost-benefit ratio 30 years	11.5	16.8	27.6	40.5
Discounted Payback Period	8.0	5.9	4.0	2.8

Note: the discount rate applied to future costs is 6% for an annuity factor of 1.085 (Appendix 8.3)

Table 6.2 Regional variations in energy and capital costs (intermediate-floor flat)

	<i>Antofagasta</i>	<i>Santiago</i>	<i>Puerto Montt</i>	<i>Punta Arenas</i>
Extra-capital costs USD/m ²	24	36	40	50
Energy savings kWh/m ² year	27.2	84.9	118.4	230.3
Extra-capital costs per saved energy kWh/m ² year	0.9	0.4	0.3	0.2
Cost-benefit ratio 10 years	3.3	6.3	7.9	12.3
Cost-benefit ratio 30 years	25.3	52.6	66.1	102.8
Discounted Payback Period	4.3	2.2	1.8	1.2

Note: the discount rate applied to future costs is 6% for an annuity factor of 1.085 (Appendix 8.3)

adequate amounts of fresh outside-air are provided (starting from 20–30 m³/h per person), together with controllable means for natural ventilation improved building designs contribute as well to enhance indoor air-quality. Furthermore, excess pollutant concentrations due to fuel combustion for space-heating can be virtually or completely eliminated by substituting conventional heaters with electric radiators that will cost significantly less to run over time (Figure 6.1).

Avoided combustion emissions: from savings in space-heating energy are worth for considering wide application of naturally conditioned dwellings countrywide. For improved standard detached houses avoided air-pollutant emissions, including PM_{2.5}, CO, NO₂ and SO₂, range annually from the warmest to the coolest location in the order of 18–128 mg/m² per dwelling. Since

these are around 88–98% of current emissions, low-energy dwellings can be mass deployed for reducing excess outdoor pollution due to residential space heating in several cities of different regions. Similar percentages in saved carbon dioxide emissions, ranging 10–60 kgCO₂/m² year, suggest that further scope for reducing carbon emissions of residential buildings lies within other lifecycle stages of buildings such as building manufacturing and construction.

The findings from simulations allowed to set out a strategy for delivering low-energy dwellings to different locations. The planning and selection of a suitable construction system for building naturally conditioned dwellings led to proposing a prefabricated low-carbon dwelling prototype. The design that uses locally sourced timber showed promising potential for further research into designing the first carbon-negative residential building in the country. The prototype demonstrated that passive design techniques specified for this research project are more profitable than installing solar energy panels requiring less than half extra-capital per saved unit of energy from Santiago to the south (see Table 6.1). Considering the analysis performed for different standard and alternative prototype designs, new housing stock in the country would worth being developed into compact multi apartment buildings that can be fabricated for urban infill using high performance timber envelopes for saving and storing carbon emissions in cities (Figure 6.2).

Overall the proposed dwelling designs offer great potential for contributing to reduce current dependence on fossil-fuels. Projections made for this study indicate that after 5 years of implementation the government will save over 40% and 62% of the current capital cost of importing fuels for construction and operation of standard detached dwellings in locations in Santiago and Punta Arenas respectively, the equivalent of 5 and 15 thousand USD.

6.2 Contribution to Knowledge

This research advances current knowledge on improving the thermal performance of residential buildings at low extra capital costs. The focus of the contribution of this thesis is on expanding existing understanding of the effects that passive design techniques have on improving occupant thermal comfort conditions for different regions of Chile. Other relevant contributions are:

- providing evidence-based understanding on occupant thermal comfort, indoor temperature preferences and energy consumption
- achieving indoor comfort temperature ranges in naturally conditioned dwellings with minimum or no additional capital cost
- expanding understanding of the thermal performance of different building residential types and design options using conventional and alternative building materials

6.3 Recommendations for Further Work

More research would be required for corroborating the contribution of low-energy and passive design techniques in real dwellings. Further work could focus on undertaking additional experimental and monitoring studies on occupant thermal comfort through full-scale fabrication of prototypes and com-

ponents. The following research areas and specific topics of investigation are recommended for reducing residual energy demands in dwellings:

- undertaking experimental studies on occupant operation of building envelope elements for passive heating and cooling
- collecting accurate data on all-house energy use based on measurements and actual capital expenditures
- performing further research into finding ways to increase the heat storage capacity of buildings (using heavyweight structural materials and/or phase change materials such as paraffin or beeswax on finishes)
- undertaking studies on natural ventilation and passive cooling through use of windows and vents (extensive computational fluid dynamics)
- performing research into measuring the embodied energy and carbon emissions of local timber applications
- studying potential for meeting all-year household energy expenditures with mainstream on-grid solar energy and billing systems

Figure 6.2 Deployment of low-energy inner-city apartment dwellings for carbon storage in cities

Depending on specific site characteristics, prefabricated low-carbon residential timber apartments of 3 to 8 storeys can be deployed over existing urban infrastructure, brownfield and public vacant plots to turn new dwelling stocks into carbon sink. For sites with limited choice of orientation and/or solar access, trade-off designs proposed for this study can be applied to optimise performance (see design options and specifications for these and other constraints in Table 4.2).



At a national level, further research would be of great value by advancing through the following research lines:

- establishing indicators for quantifying hidden fuel poverty due to inability to access acceptable indoor temperatures in dwellings
- developing an adaptive model of thermal comfort for further understanding occupant temperature preferences and fuel consumption for space thermal conditioning
- undertaking sensitivity analysis to assess vulnerability to local climate changing effects and incidence of overheating due to increase in residential apartment stocks

7 References

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8 Appendices

8.1 Field Studies and Instrumentation

The fieldwork undertaken for this research project was planned for accomplishing different objectives based on two sets of field instrumentation. The first set refers to a series of questions included in a *household survey* to assess occupant thermal comfort and fuel consumption patterns (Table 8.1). The second set involved different monitoring and measuring equipment, including standalone *data-loggers* for recording indoor space temperatures and instant-reading *thermometers* for registering occupant thermal sensation (Figure 8.1). The fieldwork was carried out during winter 2011 involving data gathered for a total of 200 households from *Olga Leiva II* and *Olga Leiva IV*, state housing developments *located* on the eastern outskirts of Santiago in Central Chile.

Table 8.1 shows a sample of the most relevant questions included in the survey. This was carried out by means of direct interviews with different household occupants randomly selected for a period of two months from July

Table 8.1 Occupant thermal comfort and fuel consumption survey

1. Occupant description

1.1 Gender: male ☐ female ☐

1.2 Age:

1.3 Occupant location:

1.4 Occupant clothing (refer to the attached Table 1.1)
clothing:

1.5 Activity level (refer to the attached Table 1.1)

resting ☐ lightly active ☐ active ☐ highly active ☐

met 0.7-1.0 1.1-2.0 2.1-3.0 3.1-4.0

2. Instant temperature measurements

2.1 measurements: outdoor temperature °C room temperature °C

3. Indoor thermal comfort perception

3.1 Indicate how do you perceive the temperature in the room at this moment?

hot ☐ warm ☐ slightly warm ☐ neutral ☐ slightly cool ☐ cool ☐ cold ☐

+3 +2 +1 0 -1 -2 -3

3.2 Indicate how do you perceive the temperature in the house in winter?

hot ☐ +3 warm ☐ +2 slightly warm ☐ +1 neutral ☐ 0 slightly cool ☐ -1 cool ☐ -2 cold ☐ -3

3.3 Indicate how do you perceive the temperature in the house in summer?

hot ☐ +3 warm ☐ +2 slightly warm ☐ +1 neutral ☐ 0 slightly cool ☐ -1 cool ☐ -2 cold ☐ -3

4. Tenure of appliances

space-heating

gas radiator (LPG) ☐ n° ☐ location ☐
 gas radiator (NG) ☐ n° ☐ location ☐
 kerosene radiator ☐ n° ☐ location ☐
 electric heater ☐ n° ☐ location ☐
 Other appliances ☐ ☐
 television ☐ n° ☐ location ☐
 fridge ☐ n° ☐ location ☐

space-cooling

cooling fan ☐ n° ☐ location ☐
 air conditioner ☐ n° ☐ location ☐
 computer ☐ n° ☐ location ☐
 kitchen ☐ n° ☐ location ☐

5. Use of appliances and windows

5.1 indicate the time the heating is on in winter?

☐
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

5.2 indicate the time the cooling is on in summer?

☐
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

5.2 indicate the time windows are opened in winter?

☐
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

6. Fuel capital expenditures and income

6.1 expenditure on heating (last month):

6.2 monthly expenditure on cooling in summer:

6.3 electricity bill

kWh ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
 Aug Sep Oct Nov Dec Jan Feb Mar Apr Jun Jul

6.4 gas bill (specify type):

kWh ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
 Aug Sep Oct Nov Dec Jan Feb Mar Apr Jun Jul

6.5 household income (last month):

7. Household occupation

7.1 indicate the number of occupants in the house

☐
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24



a)



b)

Figure 8.1 Field measurement instrumentation

a) temperature data-logger TGP-4017 (Tinytag, 2011); b) instant-reader thermo-hygrometer (Testo 626).

8.2 Thermal Properties of Building Materials

Thermophysical characteristics of building materials are retrieved from latest national standards and product data specifications (**Table 8.2**). Detailed data for building thermal computational modelling can be consulted in technical manuals commissioned by the ministry of housing (Bustamante et al., 2007) based on measurements contained in Chilean standard NCh-853 (INN, 2007) and officially approved construction assemblies (DITEC-MINVU, 2007).

Table 8.2 Thermophysical properties for different building materials

	<i>Thermal Conductivity</i>	<i>Density</i>	<i>Specific Heat</i>	<i>Reference thickness</i>	<i>Heat capacity</i>
	W/mK	Kg/m ³	J/kg K	m	Wh/m ³ K
Structural building materials					
CLT (insigne pine)	0.10	410	2,800	0.09	29.2
reinforced concrete	1.63	2,400		0.10	62.4
solid-clay brick	0.90	2,100		0.14	64.7
ceramic brick					
aerated concrete	0.15	350		7	10.2
Insulation materials					
polystyrene	0.04	10		0.1	1.2
recycled cellulose					
insulated plaster	0.09	350		0.02	1.5
Finishes					
plaster	0.56	2,000		0.02	10.4
plasterboard	0.24	650		0.01	1.6

8.3 Capital Costs of Construction and Operation

8.3.1 Construction Costs: are estimated following standard procedures applied by the Chilean ministry of housing for economic evaluation of public projects (DITEC- MINVU, 2009). The appraisal method is based on estimations of unitary building costs which include the costing of: building materials, labour, equipment and overheads. Present prices of building materials from different local suppliers and labour costs are obtained from the national construction advisory service considering a social tax rate of 29% (ONDAC, 2017). Each construction item considered for estimation is broken down as follows:

<i>Window (1000x1000mm)</i>	<i>Unit</i>	<i>Quantity</i>	<i>Unitary cost</i>
			USD
aluminium window, double slash	unit	1	57.7
metal screw (1x8 inch)	unit	10	0.05
dowel (6mm)	unit	10	0.02
glass silicone	unit	0.4	4.19
overheads	%	0.03	61.0
carpenter	HD	0.15	32.0
helper	HD	0.15	13.3
social discount rate	%	0.29	6.80
	unit	1	65

Table 8.2 and **8.3** show total building costs estimated for standard multi-unit detached and apartment developments of 16 units. Quantifications of building materials are derived from the standard base case dwelling (see detailed plans and specifications in Figure 3.6).

Table 8.3 Building capital cost for multi-dwelling developments

<i>Single-story detached houses (16 units)</i>	<i>Unit</i>	<i>Quantity</i>	<i>Unitary cost</i>	<i>Total</i>
			USD	USD
Building structure				
concrete: foundations	m ³	15.53	79	19,639
gravel bed (e=70mm)	m ²	67.54	3	2,711
polythene (e=3mm)	m ²	67.54	1	904
concrete ground slab (e=100mm)	m ³	67.54	20	21,691
concrete: posts and beams	m ³	2	395	12,632
exterior wall brick structure	m ²	62	45	44,802
interior wall brick structure	m ²	11.83	45	8,549
interior timber-frame partitions	m ²	36	16	9,394
roof timber-frame structure	m ²	82.9	25	33,281
roof lining	m ²	82.9	25	33,281
Windows and doors				
windows (1000x1000mm)	unit	6	65	10,869
windows (500x800mm)	unit	1	56	3,883
windows (500x500mm)	unit	1	57	4,577
exterior doors	unit	1	107	2,260

interior doors	unit	4	117	17,236
Finishes				
wall insulation (e=25mm)	m ²	85.5	8	903
roof insulation (e=80mm)	m ²	82.9	3	910
waterproofing walls	m ²	85.5	3	1,706
concrete screed (e=20mm)	m ²	67.54	2	7,494
Total (16 units)				225,708
per dwelling				14,107

Table 8.4 Building capital cost for multi apartment developments

<i>4 storeys apartment building (16 units)</i>	<i>Unit</i>	<i>Quantity</i>	<i>Unitary cost</i> USD	<i>Total</i> USD
Building structure				
concrete: foundation	m ³	73.46	79	5,806
gravel bed (e=70mm)	m ²	67.54	3	678
polythene (3mm)	m ²	67.54	1	226
concrete: ground slab (e=100mm)	m ³	67.54	20	5,423
concrete: posts and beams	m ³	51.12	395	20,180
concrete: inmdte. slabs (e=100mm)	m ²	6.72	406	32,711
exterior wall brick structure	m ²	1015.68	45	45,872
interior wall brick structure	m ²	11.83	45	8,549
interior wall timber-frame	m ²	36	16	9,394
roof structure timber-frame	m ²	82.9	25	8,320
roof lining	m ²	82.9	25	8,320
staircase core	unit	2	3999	7,999
Windows and doors				
windows (1000x1000mm)	unit	6	65	6,223
windows (500x800mm)	unit	1	56	903
windows (500x500mm)	unit	1	57	910
exterior doors	unit	1	107	1,706
interior doors	m ²	4	117	7,494
Finishes				
wall insulation (e=50mm)	m ²	992.04	2	2,074
roof insulation (e=80mm) mineral wool	m ²	82.9	3	971
waterproofing walls	m ²	992.04	3	3,319
concrete screed (e=20mm)	m ²	67.54	2	226
Total (16 units)				179,336
per dwelling				11,209

Table 8.5 shows unitary building costs used for improving the thermal performance of standard dwellings and design of prefabricated timber prototypes (see detailed plans and specifications in Figure 5.2, 5.3, 5.4).

Table 8.5 Unitary construction cost for different building materials

	<i>Unit</i>	<i>Unitary cost</i> USD
Structural building materials		
reinforced concrete (e=100mm)	m ²	1.89
cross-laminated timber panels (e=90mm)	m ²	2.08
structural insulated panels (e=89mm)	m ²	0.48
timber-frame partitions (2x3")	m ²	0.86
solid clay brick	m ²	0.72
ceramic brick	m ²	1.08
cellular concrete (e=75mm)	m ²	0.82
Windows		
PVC-frame windows (1000 x 1000 mm)	unit	5.65
PVC-frame windows (900 x 2000 mm)	unit	7.52
PVC-frame windows (1500 x 2000 mm)	unit	8.08
PVC-frame windows (2000 x 2000 mm)	unit	9.56
timber-frame shutter (e= 20mm)	m ²	1.28
window frame vents	unit	0.50
timber louver screen	m ²	1.54
Insulation materials		
polystyrene (e=50mm)	m ²	0.10
polystyrene (e=80mm)	m ²	0.16
polystyrene (e=100mm)	m ²	0.18
recycled cellulose		
insulated plaster (e=25mm)	m ²	0.19
Kit on-grid 3kW: 12 panels (260W), inverter (3kW)	unit	9,450
Kit on-grid 15kW: 60 panels (260W), inverter (15kW)	unit	8,540
Finishes		
plaster (e=25mm)	m ²	0.30
plasterboard (e=10mm)	m ²	0.10

8.3.2 Energy Costs: are estimated through different stages of the supply chain to final household users. The capital costs incurred by the government for importing and producing energy for domestic supply are given in **Table 8.6**, based on parity prices defined by the national institute of statistics (INE, 2014). The table also shows historical price escalation rates for projection of future energy costs based on 1990-2015 time-series (CNE, 2016).

Table 8.6 Government energy costs and historical escalation rates

<i>Fuel type</i>	<i>Government supplied energy (USD/kWh)</i>	<i>Energy price escalation rate (%)</i>
<i>Firewood</i>		
<i>Domestic kerosene</i>		13.3
<i>Liquefied petroleum gas (LPG)</i>	0.054	8.2
<i>Natural gas (NG)</i>	0.068	8.4
<i>Electricity</i>	0.080	

Note: LPG, NG and kerosene are imported and electricity is produced from hydro sources

Table 8.7 gives typical conversion factors for estimating the costs of delivered and useful energy for residential space-heating. The calorific values of fuels for conversion into kilowatt-hours are derived from data by the national energy commission (CNE, 2016). The technical efficiencies of typical space-heating appliances are retrieved from laboratory measurements commissioned by the national consumer service (DICTUC, 2010).

Table 8.7 Delivered and useful energy by type of space-heater

<i>Appliance system</i>	<i>Calorific value relative to electricity</i>	<i>Delivered energy USD/kWh</i>	<i>Efficiency of appliance %</i>	<i>Useful energy USD/kWh</i>
Room heaters				
firewood closed heater	2.86	0.08	0.60	0.11
gas radiator (LPG)	12.9	0.18	0.70	0.26
kerosene radiator	10.2	0.13	0.70	0.17
electric room heater	1.00	0.19	1.00	0.19
Central heating				
conventional boiler (NG)	9.77	0.21	0.70	0.30

Sources: (SERNAC, 2016) for prices of firewood, LPG, NG and kerosene; Chilectra (2015) for price of electricity, based on general tariff (1A)

8.4 Embodied Energy and Carbon Dioxide Emissions

8.4.1 Building Construction: projections made in this study focus on estimating the embodied energy and carbon emissions associated to building manufacturing and operation considering a useful life of 30 years. The embodied energy indices for construction of standard dwellings are considered marginal as typically found below 2% of useful life energy use (Muñoz, Zaror, Saelzer, & Cuchí, 2012). The figures in **Table 8.8** and **8.9** were estimated for the standard base case dwellings based on indices for building materials and products prepared by different sources (Hammond & Jones, 2008; Berge, 2009).

Table 8.8 Embodied energy and carbon for multi-dwelling developments

<i>Category</i>	<i>Unit</i>	<i>Quantity</i>	<i>Embodied energy</i> kWh	<i>Carbon dioxide</i> kgCO ₂
Construction				
concrete foundations	m ³	15.53	25,780	7,827
gravel bed (e=70mm)	m ³	4.72	99	148
polythene (3mm)	kg	184.3842	4,241	358
concrete ground slab (e=100mm)	m ³	6.75	11,205	3,402
concrete posts and beams	m ³	2	3,320	1,008
exterior wall brick structure	m ³	8.68	7,230	1,910
interior wall brick structure	m ³	1.66	1,383	365
interior timber-frame partitions (2x3")	m ³	8.04	1,029	201
roof timber-frame structure	m ²	82.9	13,264	3,067
roof lining	m ²	82.9	1,326	249
Finishes				
wall insulation (e=25mm) insulated plaster	m ³	2.14	696	90
roof insulation (e=80mm) mineral wool	m ³	6.6	2,224	554
waterproofing walls	kg	240.55	5,533	467
concrete screed (e=20mm)	m ³	1.35	855	420
Total			78,184	20,065
per dwelling			1,117	287

Note: 5 storeys 15 dwelling units reinforced concrete brick masonry , timber frame

Table 8.9 Embodied energy and carbon for multi-apartment developments

<i>Category</i>	<i>Unit</i>	<i>Embodied energy</i> kWh/m ³	<i>Carbon dioxide</i> kgCO ₂ /m ³	<i>Total</i>
Construction				
foundations	m ³			
ground floor slab	m ³			
intermediate floor slab				
structural walls	m			
partition walls	m			
roof structure	m			

Finishes

exterior insulation
plasterboard

Total

per dwelling

Note: 5 storeys 15 dwelling units reinforced concrete brick masonry , timber frame

Table 8.10 shows unitary embodied energy and carbon emission indices used for improved dwelling designs and prefabricated timber prototypes (see detailed plans and specifications in Figure 5.2, 5.3).

Table 8.10 Embodied energy and carbon for different building materials

	Unit	Embodied energy KWh	Carbon dioxide kgCO ₂	Total
Structural materials				
cross-laminated timber panels (e=90mm)	m ²	416	86	
structural insulated panels (e=89mm)	m ²			

8.4.2 Space-Heating Operation: emission factors from typical household appliances were taken from different laboratory tests performed by the Catholic University of Chile (CONAMA, 2003; DICTUC, 2010, 2011). The studies were undertaken under standard residential conditions in rooms of 20–50 m² considering 1.0 ac/h. Pollutant concentration limits for indoor air quality in residential premises can be consulted for different contaminants in WHO air-quality guidelines (WHO, 2014), and for compliance with national regulations in the supreme decree DS-594 (MINSAL, 2008).

Table 8.11 Air-pollutant emissions by type of space-heater (KWh)

Type of room heater	Carbon dioxide	Water vapour	PM _{2.5}	Sulfur dioxide	Nitrogen dioxide	Carbon monoxide
	kg CO ₂	kg H ₂ O	mg PM _{2.5}	mg SO ₂	mg NO ₂	mg CO
Room heaters						
firewood closed heater	0.39	-	0.39	3.24	0.62	3.35
gas radiator (LPG)	0.22	0.12	0.003	0.002	0.27	0.10
kerosene radiator	0.27	0.19	0.07	0.17	0.96	0.24
electric room heater	0.69	-	0.01	2.95	0.75	0.03
Central heating						
Conventional boiler (NG)	0.19					

Source: CONAMA, 2003; DICTUC, 2010, 2011.

8.5 Computational Simulations and Input Assumptions

Design variations for improving the thermal and environmental performance of dwellings were investigated through using different computational simulation tools. The effect of different design measures was assessed using TAS version 9.4 (EDSL, 2016) with hourly data obtained by location from Meteoronorm database (Meteotest, 2016). Simulation analysis performed on multi-zone dwelling models focus on performance of individual rooms (see geometry models used in the TAS 3D modeller interface in Figures 8.2 and 8.3). Extensive results of simulations performed for this thesis are available by location on full-page graphs at the end of the section following a brief description of the input assumptions used in the studies.

8.5.1 Weather data

The weather data files provided in Table 8.12 were obtained from Meteoronorm software version 7.1 (Meteotest, 2016). The datasets used for simulations in TAS were generated using locally recorded measurements from meteorological stations registered in the World Meteorological Organisation (WMO) (see station number and measurement period in the table). The weather files were downloaded on a typical meteorological year format (TMY) and converted into an hourly year-reference dataset using the TAS weather utility (EDSL, 2016), including 8,760 data records for dry-bulb temperature, global solar radiation, diffuse solar radiation, wind speed, wind direction, cloud cover and relative humidity. A graphical summary of relevant weather data for simulations can be consulted in monthly-diurnal average graphs at the end of the section.

Table 8.12 Weather data files and measurement periods used for simulations

<i>Weather file</i>	<i>Met station</i>	<i>°S</i>	<i>°W</i>	<i>WMO station</i>	<i>Measurement periods temperature</i>	<i>solar radiation</i>
Santiago	<i>Pudahuel</i>	33	71	855740	2000–09	1996–2005
Antofagasta	<i>Antofagasta</i>	23	70	854420	2000–09	1991–2010
Puerto Montt	<i>El Tepu</i>	41	73	857990	2000–09	1997–2013
Calama	<i>El Loa</i>	20	69	854320	1961–90	1997–2013
Copiapó	<i>Chamonte</i>	26	67	854700	1961–90	1997–2013
Valparaíso	<i>Valparaíso</i>	33	72	855580	2000–09	1962–2004
Temuco	<i>Maquehue</i>	37	73	857430	1961–90	2000–2009
Punta Arenas	<i>PuntaArenas</i>	53	71	859340	2000–09	1991–2010

8.5.2 Dwelling models

Two building models representing a single-storey detached and an intermediate-floor apartment unit in a multi-storey apartment building were used as input in TAS (see detailed plan and elevations in Figure 3.4). The models shown in Figure 8.2 and Figure 8.3 represent the base-case dwellings used for performing parametric analysis —these represent standard three-roomed dwell-

Figure 8.2 Computational model for the standard detached dwelling

Single-storey 70 m² three-room unit of minimum net glazing size (1.0 m²), and room dimensions (after HSFP, 2016).

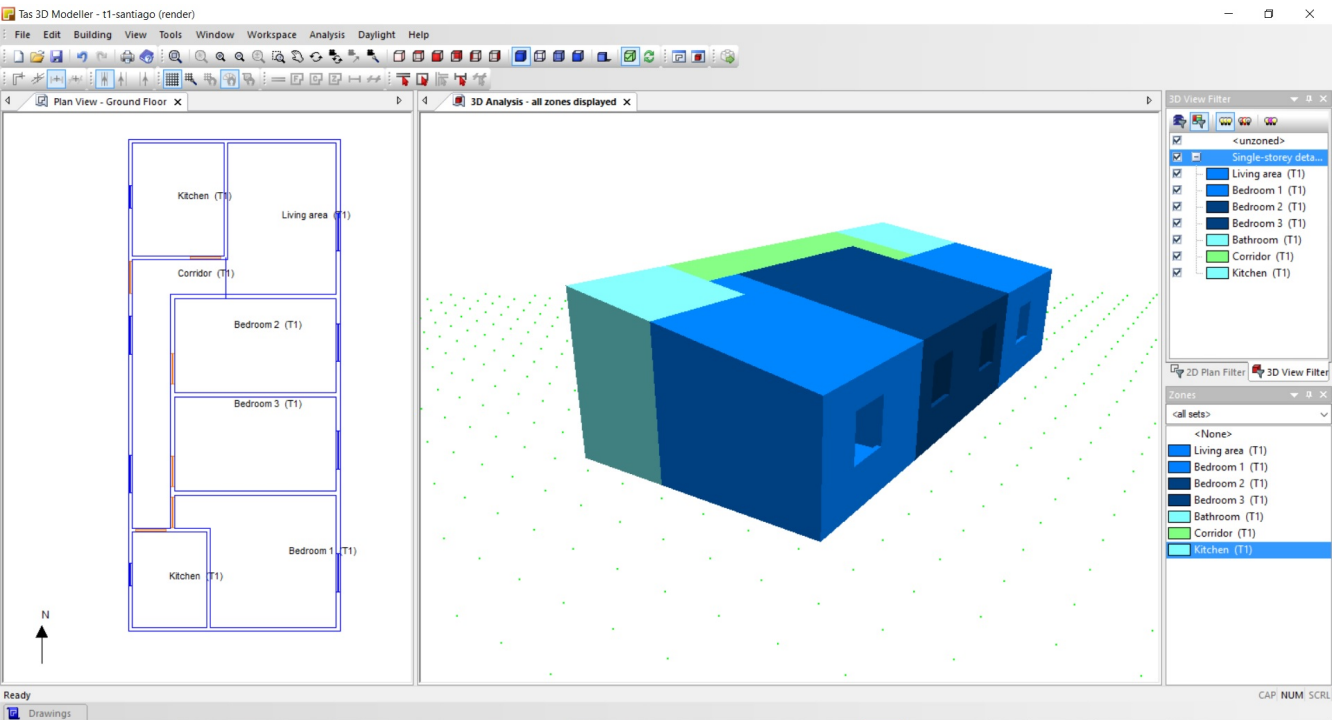
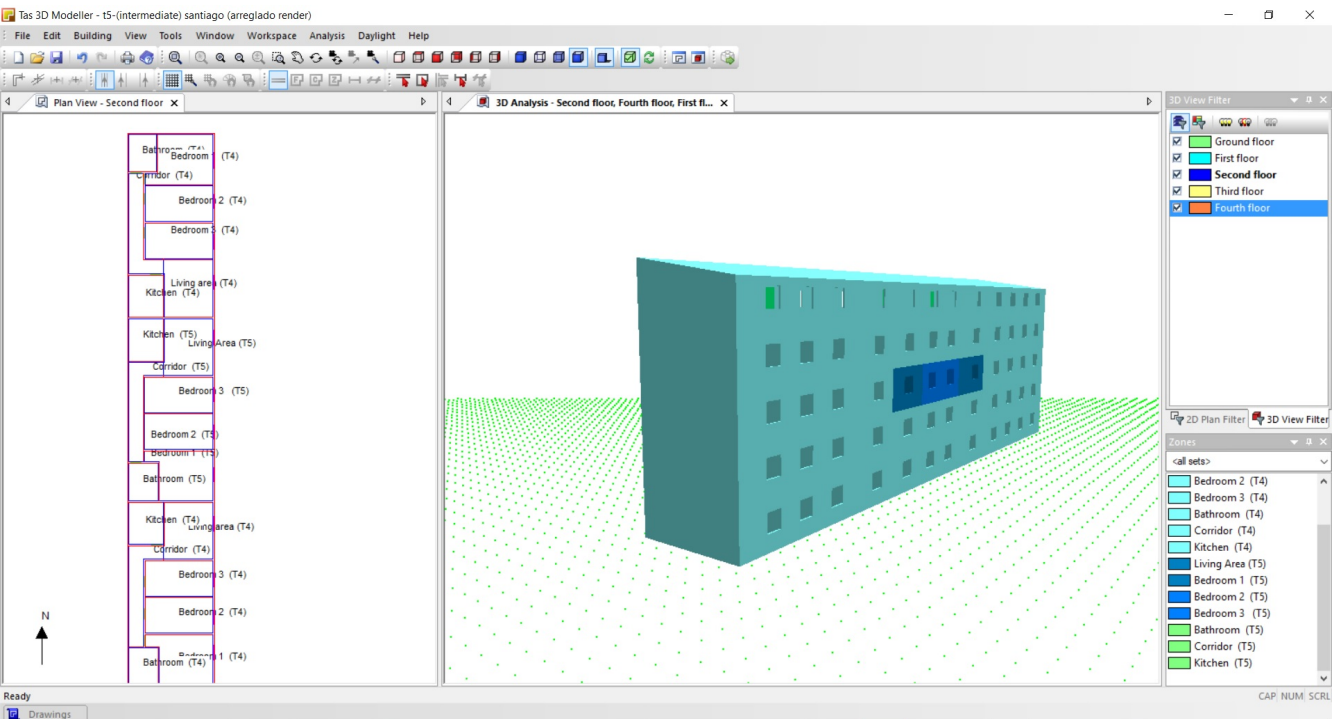


Figure 8.3 Computational model for the intermediate-floor apartment

Apartment building of 5 storeys, allowing multi-zoning for all units.



ings of 70m² habitable floor area and minimum allowable glazing size for habitable rooms. All the interior rooms in the dwellings were considered as a different zone to take into account thermal exchanges between rooms, however as highlighted in the figures for simplicity of interpretation the results of simulations focus on the performance of the living area and main bedroom.

8.5.3 Internal conditions

Each designated zone in the dwelling models was assigned with a different internal condition profile set in TAS according to specific usage characteristics (see reference household profile in Section 3.2). **Table 8.13** shows hourly input values used for air infiltration and ventilation on each zone (hourly sensible heat gains from occupancy and equipment are available in Table 3.5). The input data used for simulations are standard reference values set for comparing the effects of variations in building design (see variations in internal condition parameters in Figure 8.6, 8.8 and 8.11). To meet the target performance criteria set for simulations the following input assumptions were considered:

- *Air-infiltration*: an air exchange rate of 1.0 ac/h was set for each zone to be constant regardless of specific wind site effects (setting TAS infiltration coefficient to 1 for a fixed rate at all wind speeds)¹
- *Ventilation*: an additional air exchange rate of 0.5–1.0 ach (depending on room size) is assumed to meet a target of 30 m³/h per person in occupied rooms at any given time (see ventilation criteria in Section 3.4)

Table 8.13 Hourly air infiltration and ventilation rates

Area	Source	Room air-exchange rates ac/h																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Living area	infiltration	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	ventilation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2	2	2	2	3	3	3	-	-
Bedroom 1 (main bedroom)	infiltration	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	ventilation	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1
Bedroom 2	infiltration	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	ventilation	0.5	0.5	0.5	0.5	0.5	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	0.5
Bedroom 3	infiltration	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	ventilation	0.5	0.5	0.5	0.5	0.5	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	0.5
Kitchen area	infiltration	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Bathroom	Infiltration	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Total number of occupants		4	4	4	4	4	4	1	1	1	1	1	1	1	1	3	3	3	3	3	4	4	4	4	4

Note: indicatives values used for computational simulation estimated for the base-case dwelling of 70 m²

¹ TAS infiltration coefficient can be set between 0 and 1. 0 for direct proportionality between air infiltration and wind-speed, and 1 for fixed air infiltration at all wind-speeds (see definition in EDSL, 2011)

- *Occupancy heat gains:* of 5.0 W/m² per person in occupied rooms, 5.0 W/m² for lighting and equipment, and 10 W/m² for kitchen appliances (no additional latent heat fractions were specified)

8.5.4 Building element specification

Table 8.14 shows building element specifications for the base-case dwellings. Either for the detached or the intermediate-floor apartment the base-case model for each location was specified with standard timber frame constructions considering maximum national statutory thermal transmittances (CTR, 2007) for external walls and roof (see detailed specifications in Table 8.14). The glazing elements were specified irrespective of location to meet the minimum national allowable net glazing size for habitable rooms and considering specification of single-glazing, window aperture openings closed all time and no other operable building element assigned to run the simulations.

Table 8.14 Building element specifications for the base case

<i>Layer</i>	<i>Description</i>	<i>Thickness</i>	<i>Thermal conductivity</i>	<i>Density</i>	<i>Specific heat</i>
		mm	W/mK	Kg/m ³	J/kg K
External wall: timber-frame construction					
1 (inner)	Gypsum plasterboard (int. surf. solar absorptance= 0.4)	10	0.24	650	840
2	Air cavity (conv. coeff.=1.25 W/m ² K)	70	0.00	0.00	0.00
3	Oriented strand board (OSB)	11	0.10	800	2,093
4	Exterior vinyl cladding	2.0	0.09	350	1,000
U-value: 1.9 W/m²K					
Internal wall: plasterboard partitions					
1 (inner)	Gypsum plasterboard (int. surf. solar absorptance= 0.4)	10	0.24	650	840
2	Expanded polystyrene (EPS)	50	0.04	10	1,200
3	Gypsum plasterboard	10	0.24	650	840
U-value: 0.7 W/m²K					
Ground floor: reinforced concrete slab on grade					
1 (inner)	Reinforced concrete (surf. solar absorptance= 0.7)	100	1.63	2,400	920
2	Polythene	3.0	0.25	500	1,000
3	Compacted gravel (no fines 1: 10 *2)	500	0.81	1,700	920
U-value: 1.1 W/m²K					
Roof: timber-frame construction					
1 (inner)	Gypsum plasterboard (int. surf. solar absorptance= 0.4)	10	0.24	650	840
2	Expanded polystyrene (EPS)	80	0.04	10	1,200
3	Air cavity (conv. coeff.=1.95 W/m ² K)	70	0.00	0.00	0.0

<i>Layer</i>	<i>Description</i>	<i>Thickness</i>	<i>Thermal conductivity</i>	<i>Density</i>	<i>Specific heat</i>
		mm	W/mK	Kg/m ³	J/kg K
4	Fibercement cladding board	5	0.22	837	920
U-value: 0.4 W/m²K					
Doors: standard plywood					
1 (inner)	Plywood (insigne pine) board	3.0	0.10	410	2,805
2	Air cavity (conv. coeff.=1.25 W/m ² K)	35	0.00	0.00	0.0
3	Plywood (insigne pine) board	3.0	0.10	410	2,805
U-value: 2.5 W/m²K					
Windows: single-glazing					
1 (inner)	Clear glass (solar transmittance= 0.84)	3.0	1.0	-	-
U-value: 5.8 W/m²K					

Note: specifications based on requirements for Santiago, for other locations see Figure 4.30

Table 8.15 shows building specifications assigned for improving the base case models. Firstly, as explained for each step of the design guidelines in Section 4.2 (see also graphical summary in Figure 4.5), the timber-frame construction specified for the base-case was replaced with solid brick and cross-laminated timber constructions with interior plaster rendering (*step 1*). Statutory wall insulation (*step 2*) and room glazing size (*step 3*) were increased to achieve winter comfort requirements. As specified by location in Figure 4.30, during the cold season insulated shutters (*step 4*), and window vents (*step 5*), were applied through simulations by assigning a substitute building element and reducing the ventilation rate allocated for each zone. As specified in the table, during the warm season exterior shading louvers (*step 6*) and window openings (*step 7*) were applied by assigning in TAS a shading feature and a window aperture type respectively.

Table 8.14 Building element specifications for the improved base case

<i>Layer</i>	<i>Description</i>	<i>Thickness</i>	<i>Thermal conductivity</i>	<i>Density</i>	<i>Specific heat</i>
		mm	W/mK	Kg/m ³	J/kg K
External wall: solid-clay brick construction					
1	Interior plaster finish (int. surf. solar absorptance= 0.7)	20	1.4	2,000	940
3	Solid clay brick masonry	140	0.9	920	2,100
3	Expanded polystyrene (EPS)	80	0.04	10	1,200
4	Exterior plaster finish	5.0	0.09	350	1,000
U-value: 0.5 W/m²K					

<i>Layer</i>	<i>Description</i>	<i>Thickness</i>	<i>Thermal conductivity</i>	<i>Density</i>	<i>Specific heat</i>
		mm	W/mK	Kg/m ³	J/kg K
Internal wall: plasterboard partitions					
1 (inner)	Gypsum plasterboard (int. surf. solar absorptance= 0.7)	10	1.4	2,000	940
2	Cross-laminated timber (insigne pine wood)	70	0.04	10	1,200
3	Gypsum plasterboard	10	1.4	2,000	940
U-value: 1.2 W/m²K					
Ground floor: reinforced concrete slab on grade					
1 (inner)	Reinforced concrete (surf. solar absorptance= 0.7)	100	1.63	2,400	920
2	Polythene	3.0	0.25	500	1,000
3	Compacted gravel (no fines 1: 10 *2)	500	0.81	1,700	920
U-value: 1.1 W/m²K					
Roof: cross-laminated timber construction					
1 (inner)	Gypsum plasterboard (int. surf. solar absorptance= 0.4)	10	1.4	2,000	940
2	Cross-laminated timber (insigne pine wood)	90	0.04	10	1,200
3	Expanded polystyrene (EPS)	50	0.04	10	1,200
4	Fibrocement cladding board	5	0.22	837	920
U-value: 0.4 W/m²K					
Doors: standard insulated plywood					
1 (inner)	Plywood (insigne pine) board	3.0	0.10	410	2,805
2	Expanded polystyrene (EPS)	35	0.04	10	1,200
3	Plywood (insigne pine) board	3.0	0.10	410	2,805
U-value: 1.0 W/m²K					
Windows: single-glazing					
1 (inner)	Clear glass (solar transmittance= 0.84)	3.0	1.0	-	-
U-value: 5.8 W/m²K					
Substitute element: internal insulated shutter (applied to windows)					
1 (inner)	Vinyl coating	2.0	0.09	350	1,000
2	Expanded polystyrene (EPS)	21	0.04	10	1,200
3	Vinyl coating	2.0	0.09	350	1,000
4	Plywood (insigne pine) board	3.0	0.10	410	2,805
5	Air cavity (conv. coeff.=1.25 W/m ² K)	70	0.00	0.00	0.0
6	Clear glass	3.0	1.0	-	-
U-value: 1.1 W/m²K					

Note: specifications based on improvements for Santiago, for other locations see Figure 4.30

Figure 8.4 Monthly-diurnal average weather data for simulations

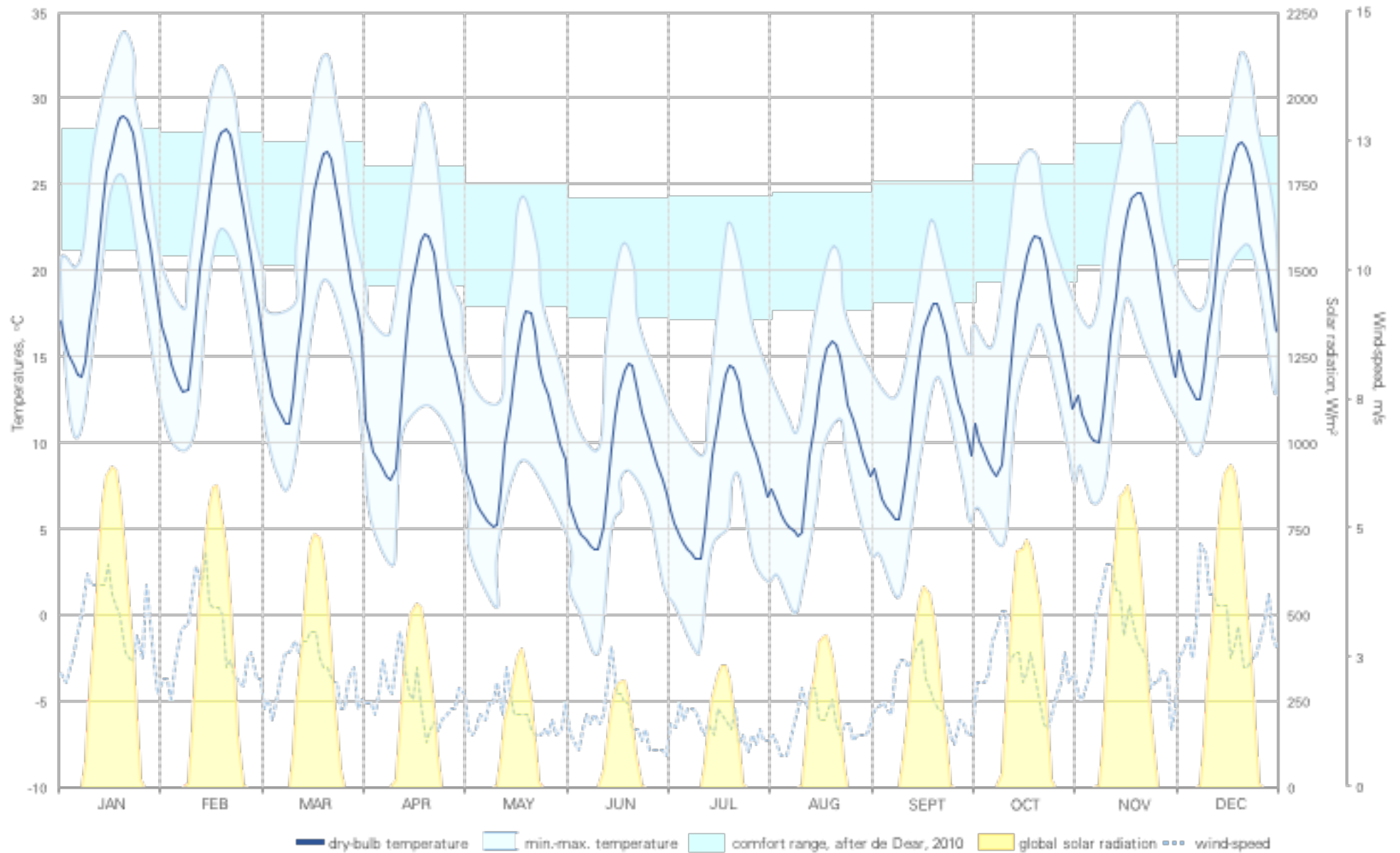


Figure 8.4.1 Monthly diurnal average weather data for Santiago

Weather dataset prepared with hourly-yearly data made available by Meteotest version 7.1 (Meteotest, 2016), for met-station *Pudahuel*, Santiago (33°S;71°W), WMO number 855740, measurement period 2000–09 (dry-bulb temperature) and 1996–2005 (solar radiation). Adaptive comfort limits estimated for mean monthly outdoor temperatures, after de Dear (2010).

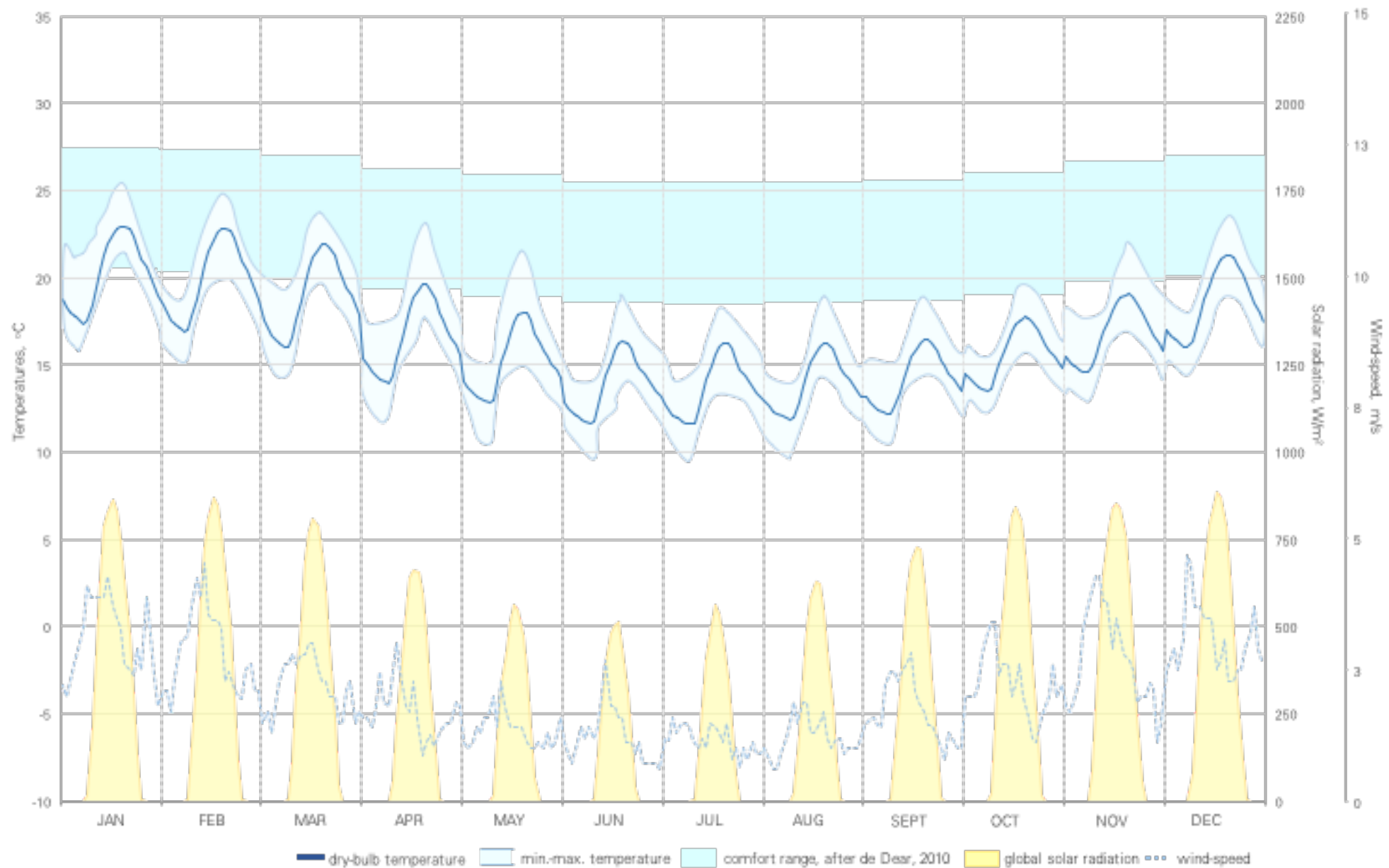


Figure 8.4.2 Monthly diurnal average weather data for Antofagasta

Weather dataset prepared with hourly-yearly data made available by Meteotest version 7.1 (Meteotest, 2016), for met-station *Antofagasta* (23°S;70°W), WMO number 854420, measurement period 2000–09 (dry-bulb temperature) and 1991–2010 (solar radiation). Adaptive comfort limits estimated for mean monthly outdoor temperatures, after de Dear (2010).

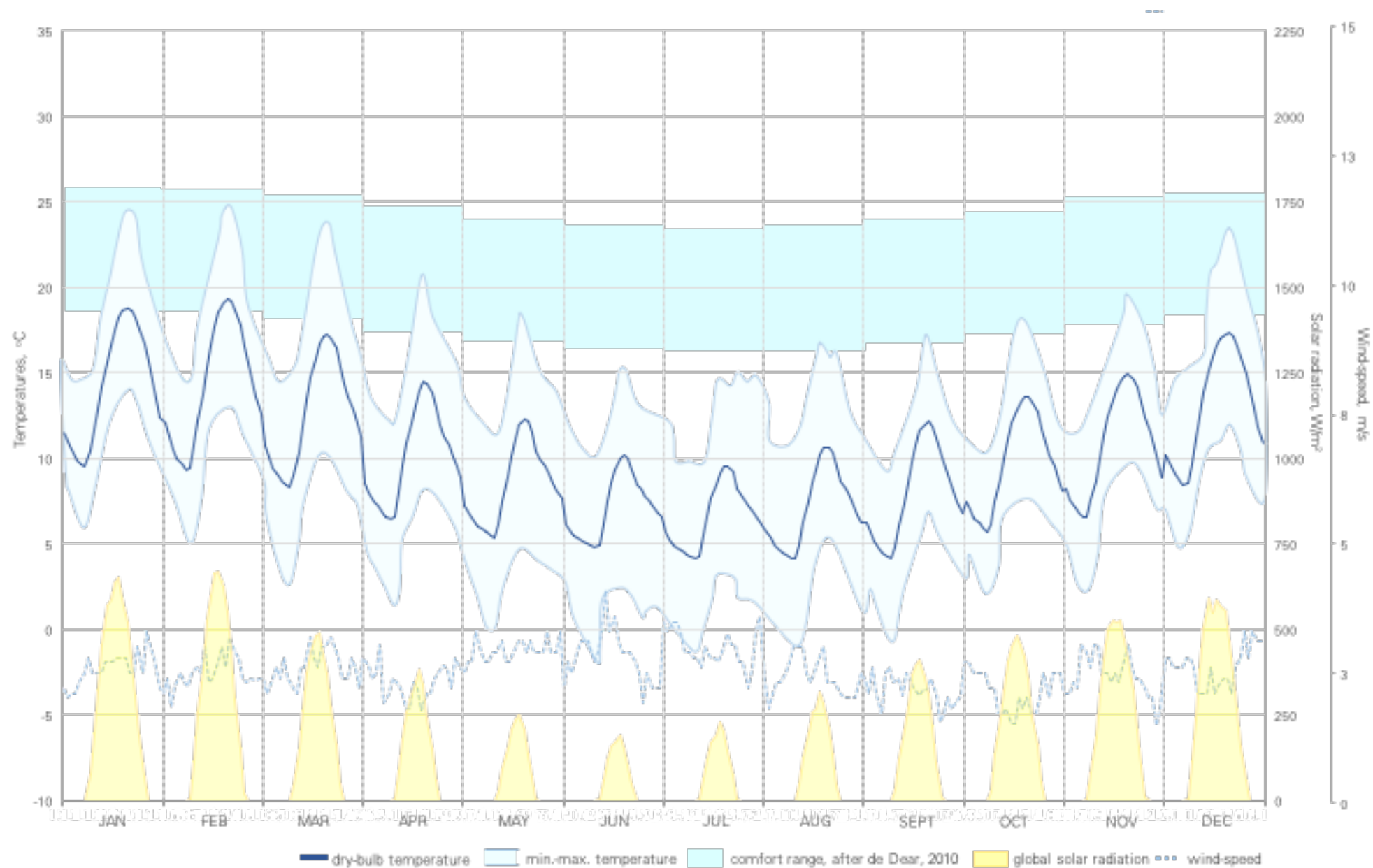


Figure 8.4.3 Monthly diurnal average weather data for Puerto Montt

Weather dataset prepared with hourly-yearly data made available by Meteotest version 7.1 (Meteotest, 2016), for met-station *El Tepu*, Puerto Montt (33°S;71°W), WMO number 857990, measurement period 2000–09 (dry-bulb temperature) and 1997–2013 (solar radiation). Adaptive comfort limits estimated for mean monthly outdoor temperatures, after de Dear (2010).

Figure 8.6 Results of building thermal simulations for Santiago (33°S), Central Interior (NCh-1079; INN, Of. 2008)

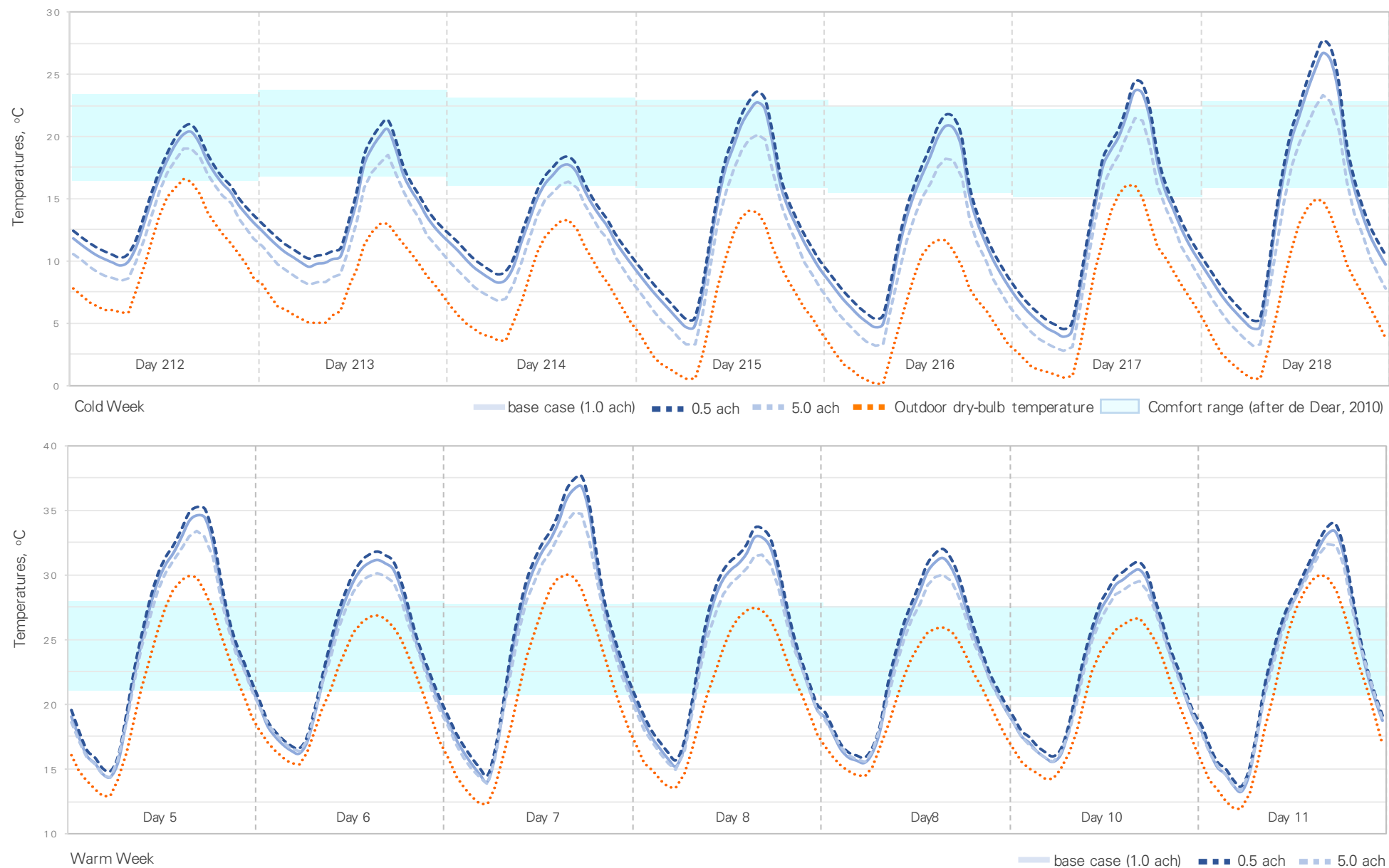


Figure 8.6.1 Effect of varying air-exchange rates (single-storey detached)

Different air-exchange rates are compared for the base-case of Santiago by changing infiltration rates in TAS. Three scenarios were investigated, based on blower door testing by Figueroa et al (2013): one for the lowest measured value of 0.5 ach, one for the average of 1.0 ach, and other for the highest value of 5.0 ach (see airtightness and ventilation criteria in section 3.4.3)

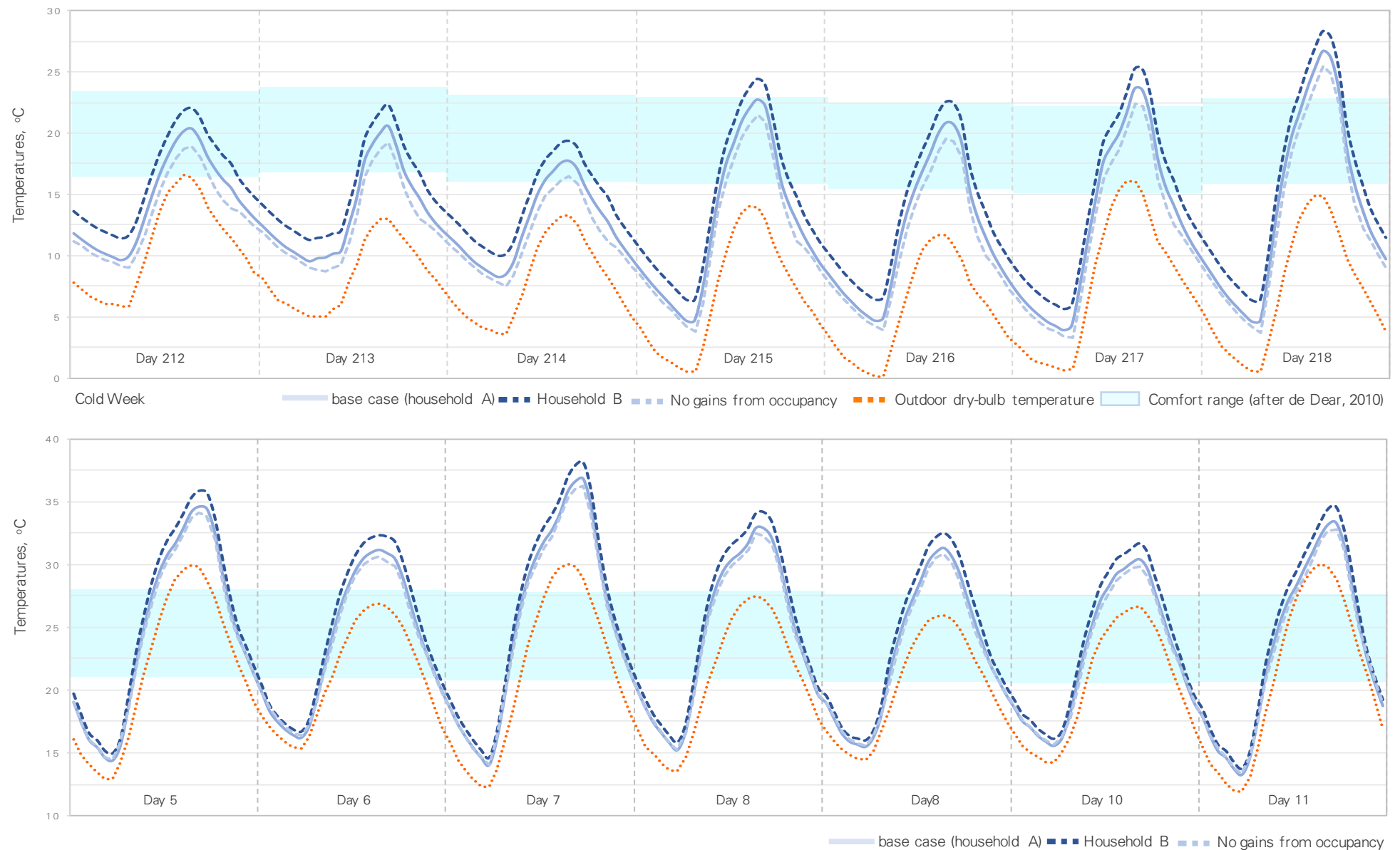


Figure 8.6.2 Effect of varying internal heat gains (single-storey detached)

Different internal heat gain loads are compared for the base-case of Santiago by changing hourly input assumptions in TAS. Three scenarios were investigated: one with no internal heat gains from occupants nor appliances; other for a household of four (*household A*), considering 5.0 W/m^2 per occupant, 5.0 W/m^2 for appliances in occupied rooms, and 10 W/m^2 for kitchen equipment (see hourly distribution in Table 3.5); and other for the same occupancy schedules (*Household B*) but increasing the number of occupants and heat gains from appliances by twofold

Figure 8.7 Parametric design improvements for the intermediate-floor apartment

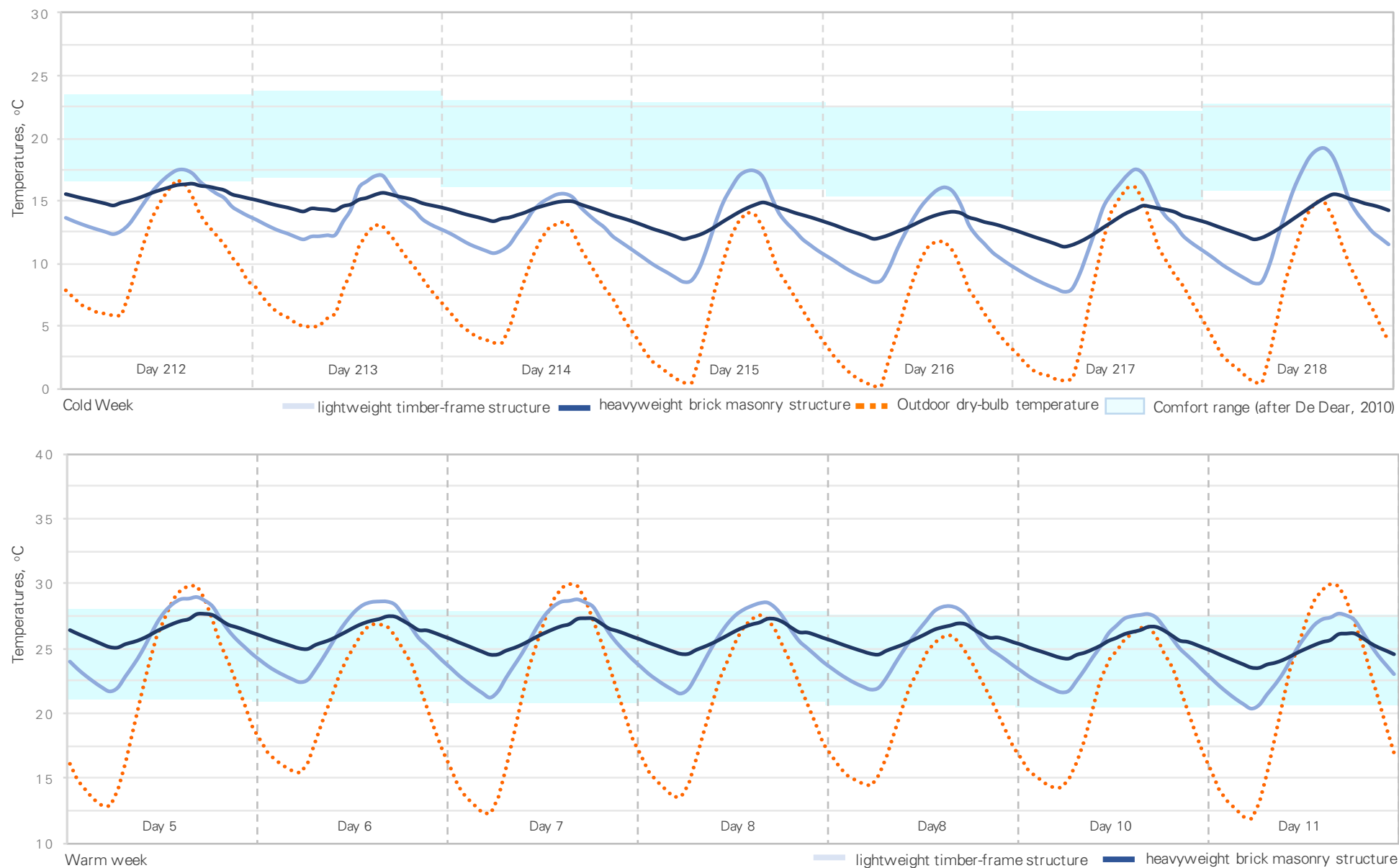


Figure 8.7.1 Effect of increasing building thermal capacity (intermediate-floor flat)

Typical timber-frame envelope structure is compared to a heavyweight masonry structure (traditional solid clay brick and light-concrete blocks with plaster finishes, see construction specifications in Figures 4.1 and 4.2). Both envelope structures consider minimum statutory insulation for exposed walls ($U=1.9 \text{ W/m}^2\text{k}$)

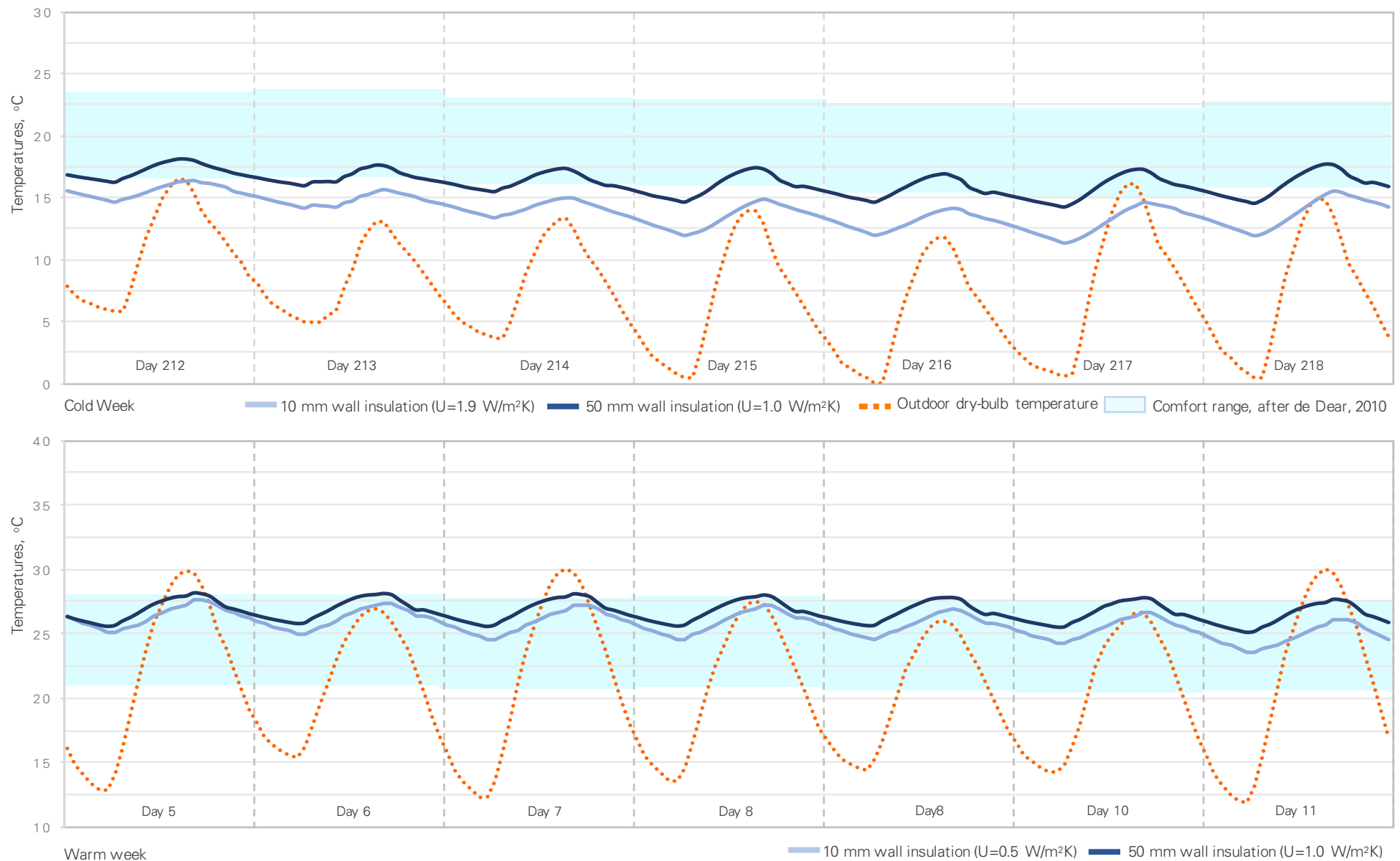


Figure 8.7.2 Effect of increasing wall thermal insulation (intermediate-floor flat)

The thermal transmittance (U-value) of exposed wall elements is decreased from 1.9 W/m²K (CLT, 2007) to 0.5 W/m²K by increasing the thickness of external insulation (expanded polystyrene board) specified from 10 to 50 mm (based on results of simulations for the living area).

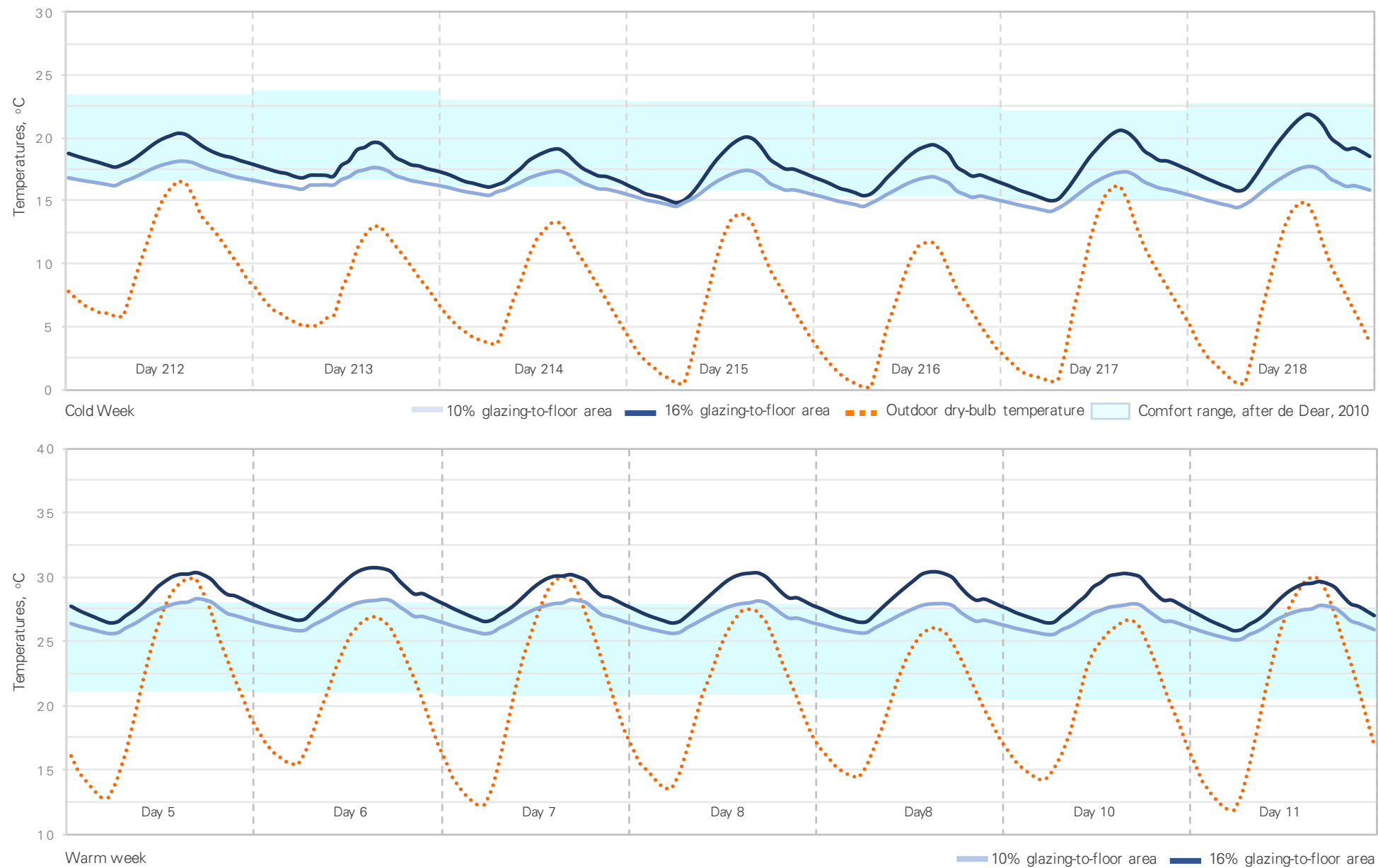


Figure 8.7.3 Effect of increasing the size of room glazing areas (intermediate-floor flat)

For the windows of the base-case dwelling oriented towards the equator, room net glazing-to-floor areas are increased from 10% to 16% (based on results for the living area).

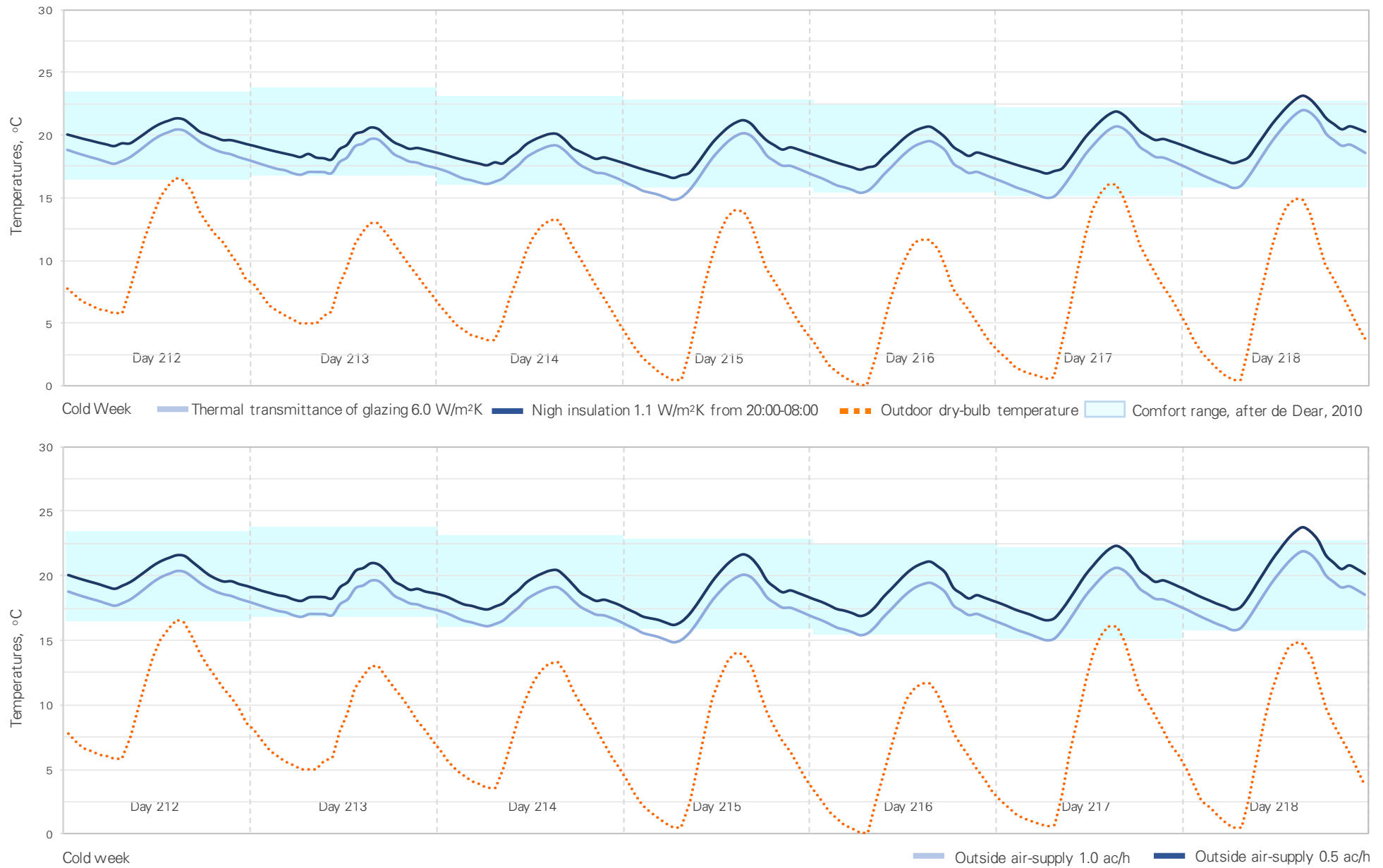


Figure 8.7.4 Effect of insulated shutters and window-frame vents (intermediate-floor apartment)

a) room thermal performance with and without use of internal blind shutters over night; b) outside air-supply rates are reduced by assuming window vents openings at minimum.

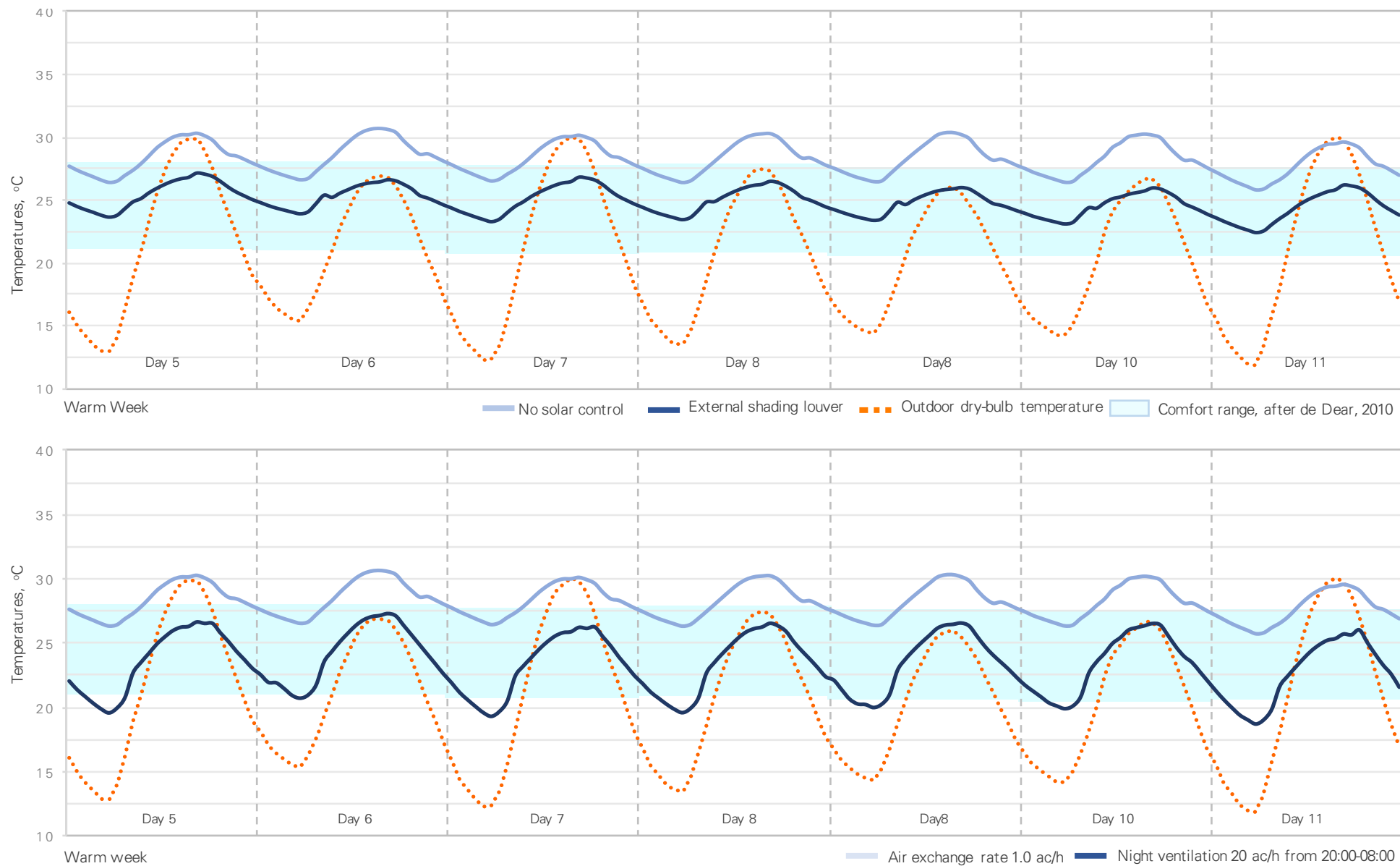


Figure 8.7.5 Effect of external shading blinds and opening windows (intermediate-floor apartment)

a) external window louvers are operated with their blinds positioned horizontally; b) half of room window area is assumed opened overnight, the equivalent of 8% room floor area (the resulting air exchange rate above is an average value obtained for the period over which windows were kept opened).

Figure 8.8 Results of building thermal simulations for Antofagasta (23°S), Northern Coast (NCh-1079; INN, Of.2008)

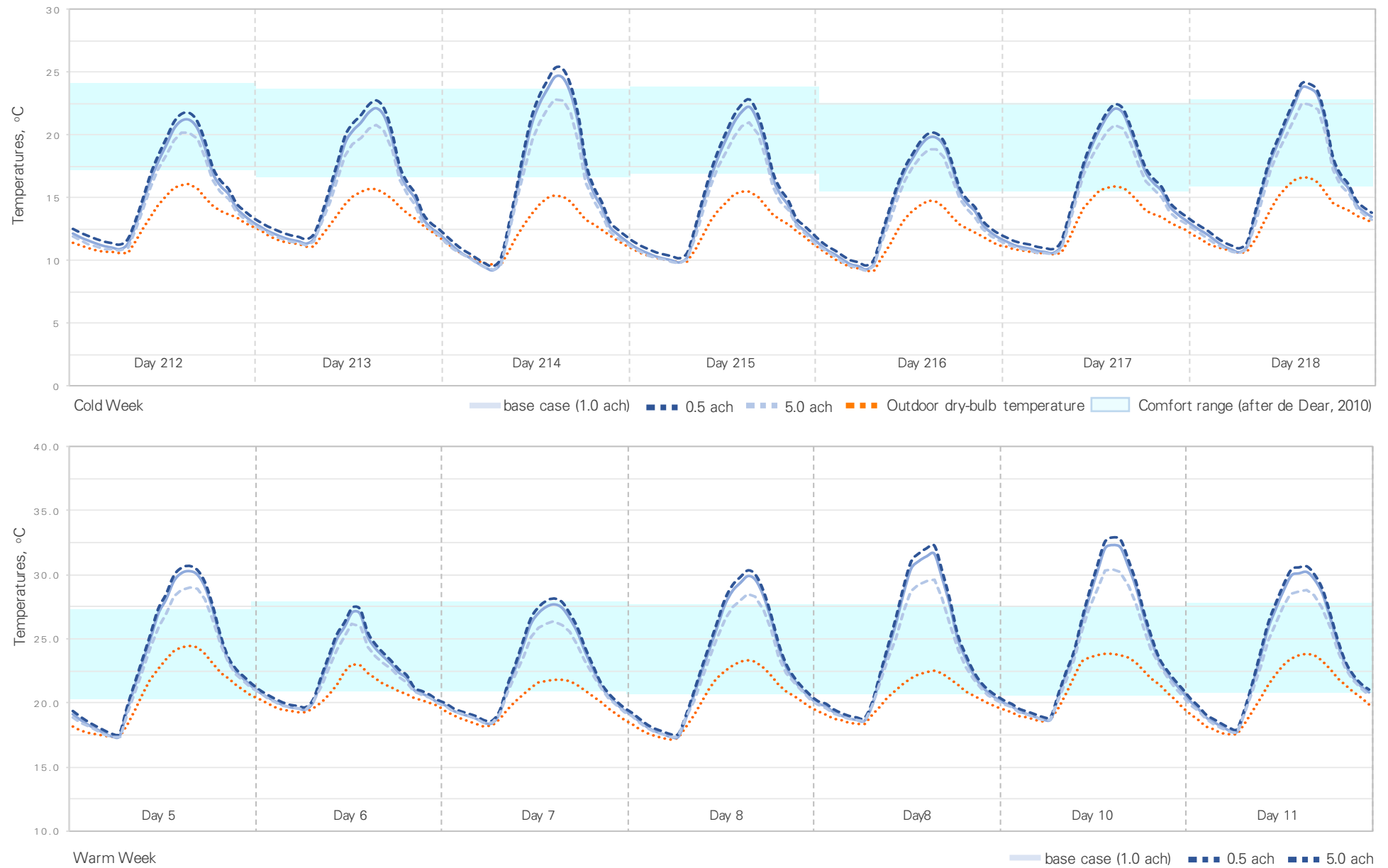


Figure 8.8.1 Effect of varying air-exchange rates (single-storey detached)

Different air-exchange rates are compared for the base-case of Santiago by changing infiltration rates in TAS. Three scenarios were investigated, based on blower door testing by Figueroa et al (2013): one for the lowest measured value of 0.5 ach, one for the average of 1.0 ach, and other for the highest value of 5.0 ach (see airtightness and ventilation criteria in section 3.4.3)

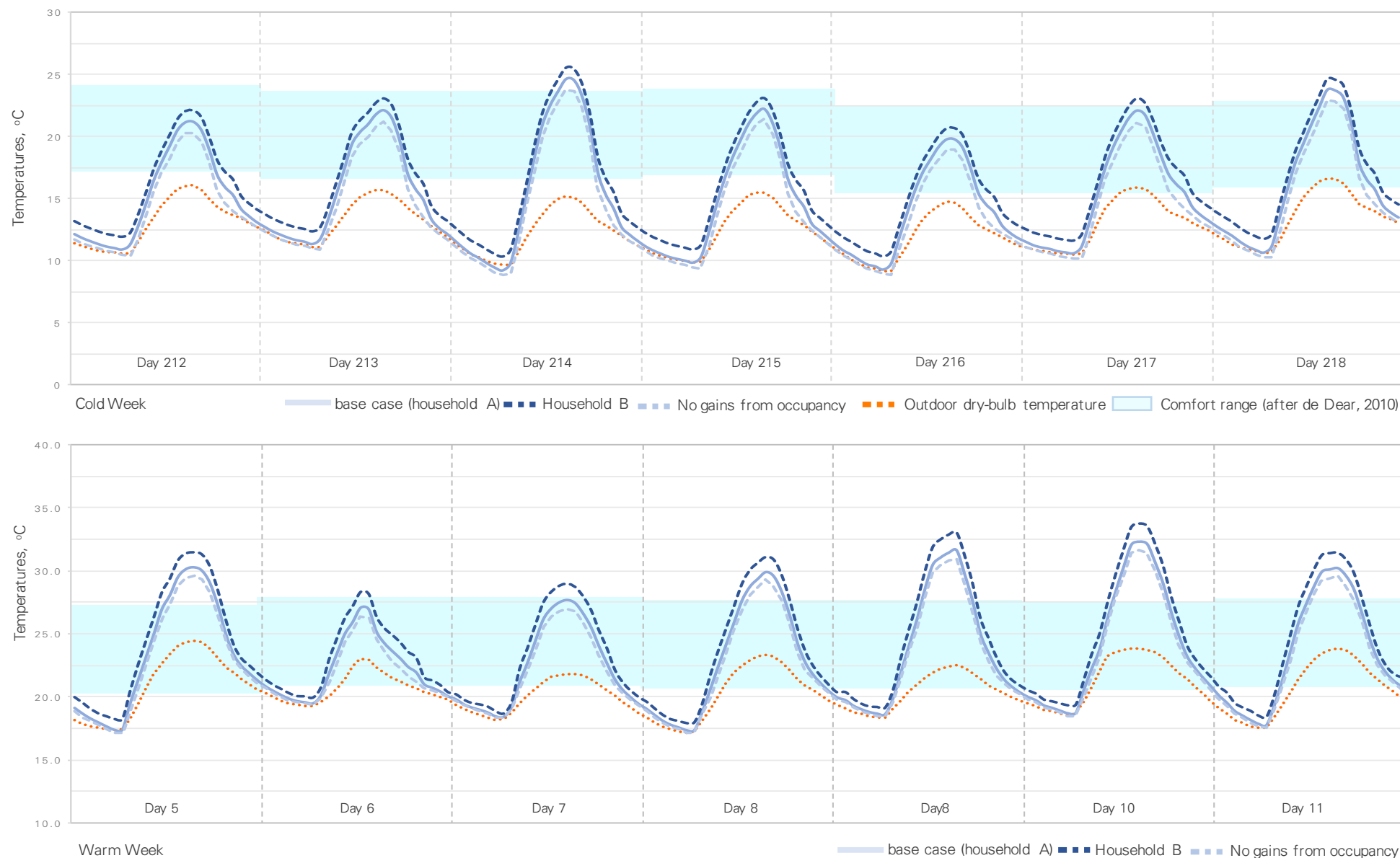


Figure 8.8.2 Effect of varying internal heat gains (single-storey detached)

Different internal heat gain loads are compared for the base-case of Santiago by changing hourly input assumptions in TAS. Three scenarios were investigated: one with no internal heat gains from occupants nor appliances; other for a household of four (*household A*), considering 5.0 W/m² per occupant, 5.0 W/m² for appliances in occupied rooms, and 10 W/m² for kitchen equipment (see hourly distribution in Table 3.5); and other for the same occupancy schedules (*Household B*) but increasing the number of occupants and heat gains from appliances by twofold.

Figure 8.9 Parametric design improvements for the single-storey detached dwelling

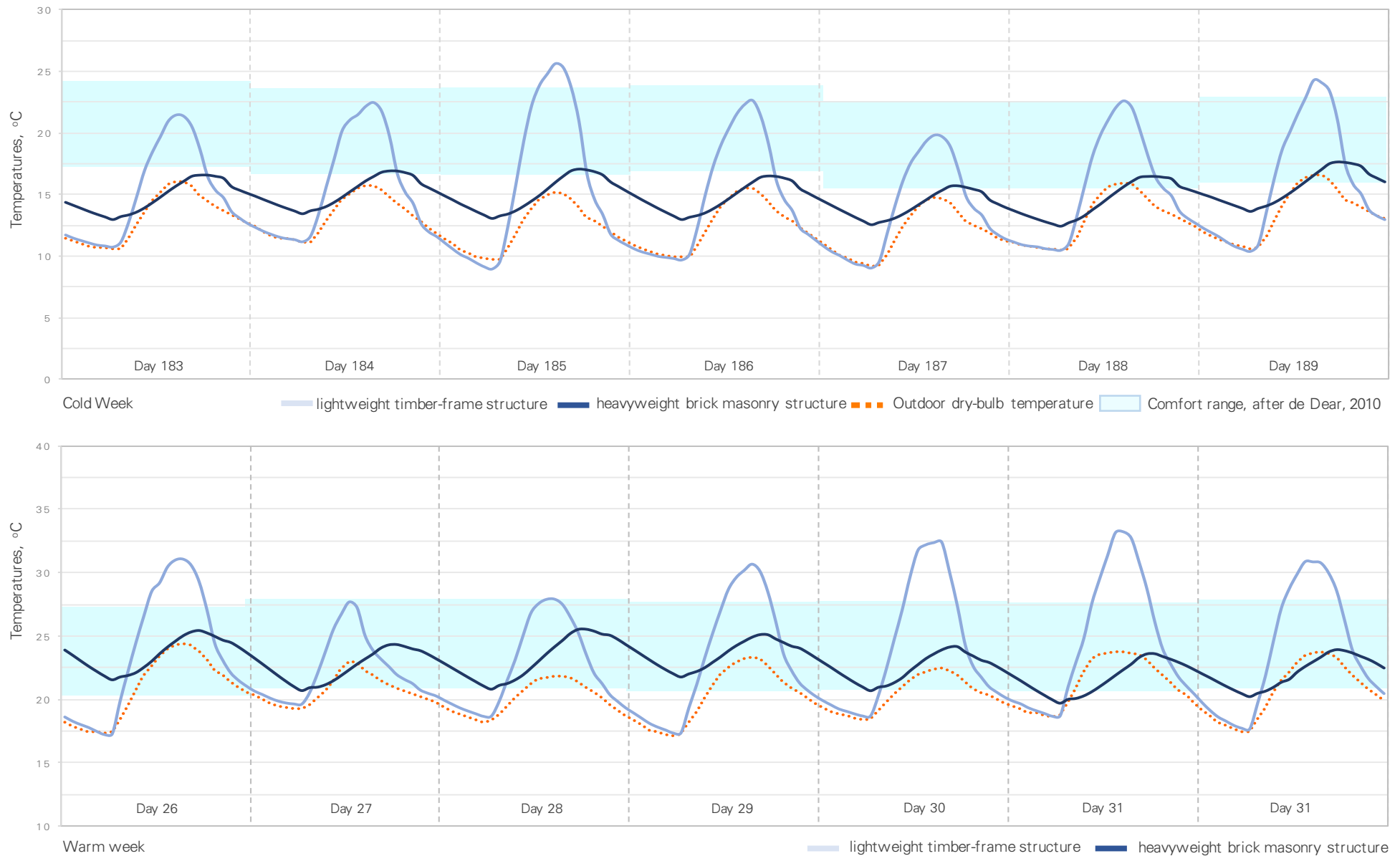


Figure 8.9.1 Effect of increasing building thermal capacity (single-storey detached)

Typical timber-frame envelope structure is compared to a heavyweight masonry structure (traditional solid clay brick and light-concrete blocks with plaster finishes, see construction specifications in Figures 4.1 and 4.2). Both envelope structures consider minimum statutory insulation for exposed walls ($U=4.0 \text{ W/m}^2\text{k}$) and roof elements ($U=0.8 \text{ W/m}^2\text{k}$).

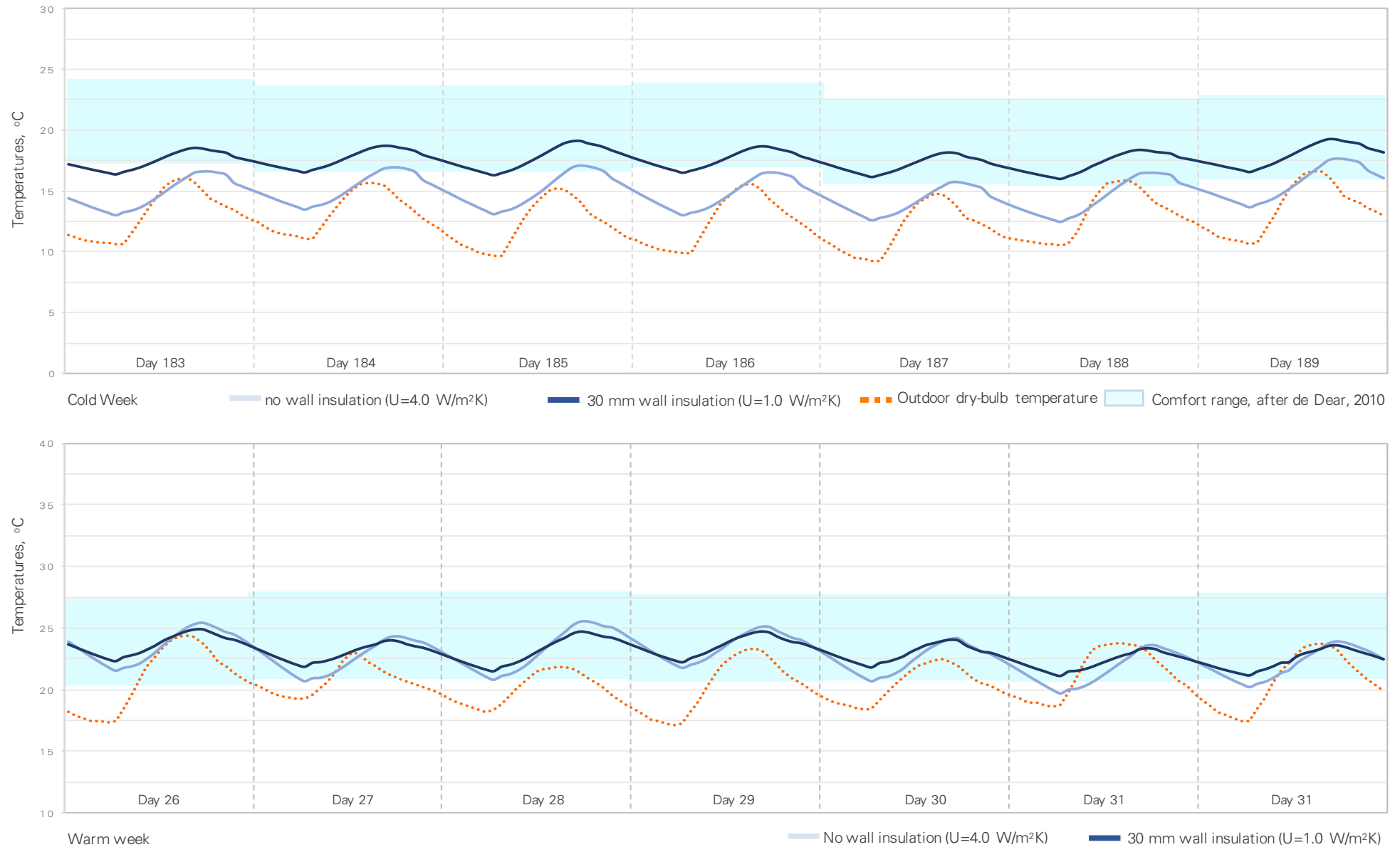


Figure 8.9.2 Effect of increasing wall thermal insulation (single-storey detached)

The thermal transmittance (U-value) of exposed wall elements is decreased from 4.0 W/m²K (CLT, 2007) to 2.0 W/m²K by adding envelope insulation (expanded polystyrene board) of 30 mm on the outside of the wall element, before the cladding (based on results of simulations for the living area).

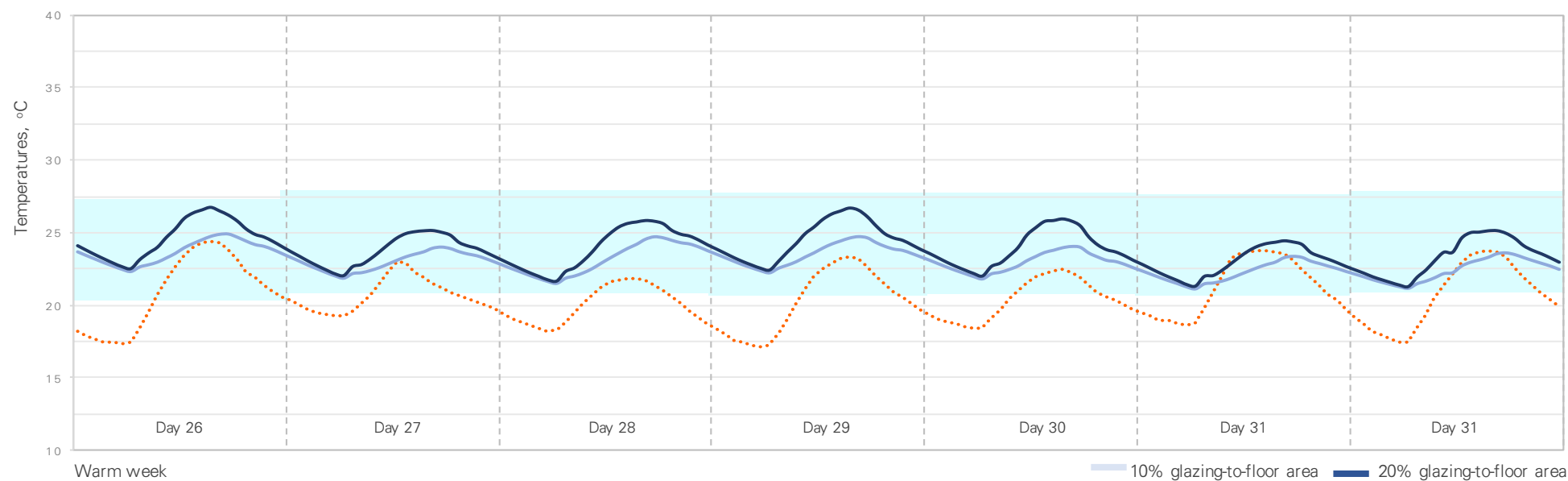
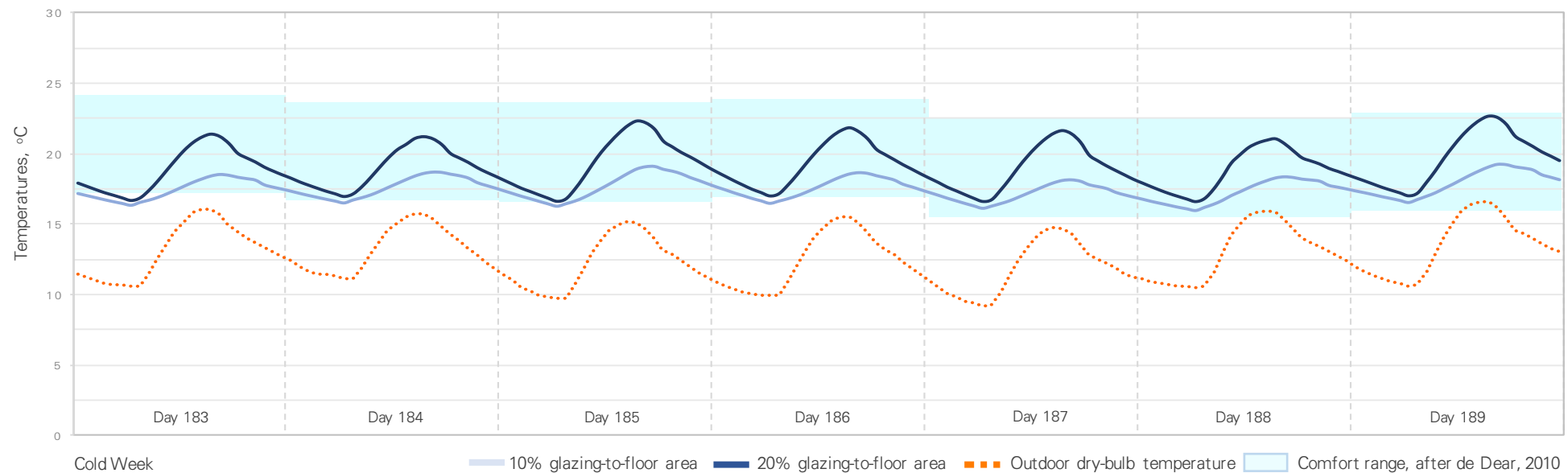


Figure 8.9.3 Effect of increasing the size of room glazing areas (single-storey detached)

For the windows of the base-case dwelling oriented towards the equator, room net glazing-to-floor areas are increased from 10% to 20% (based on results for the living area)

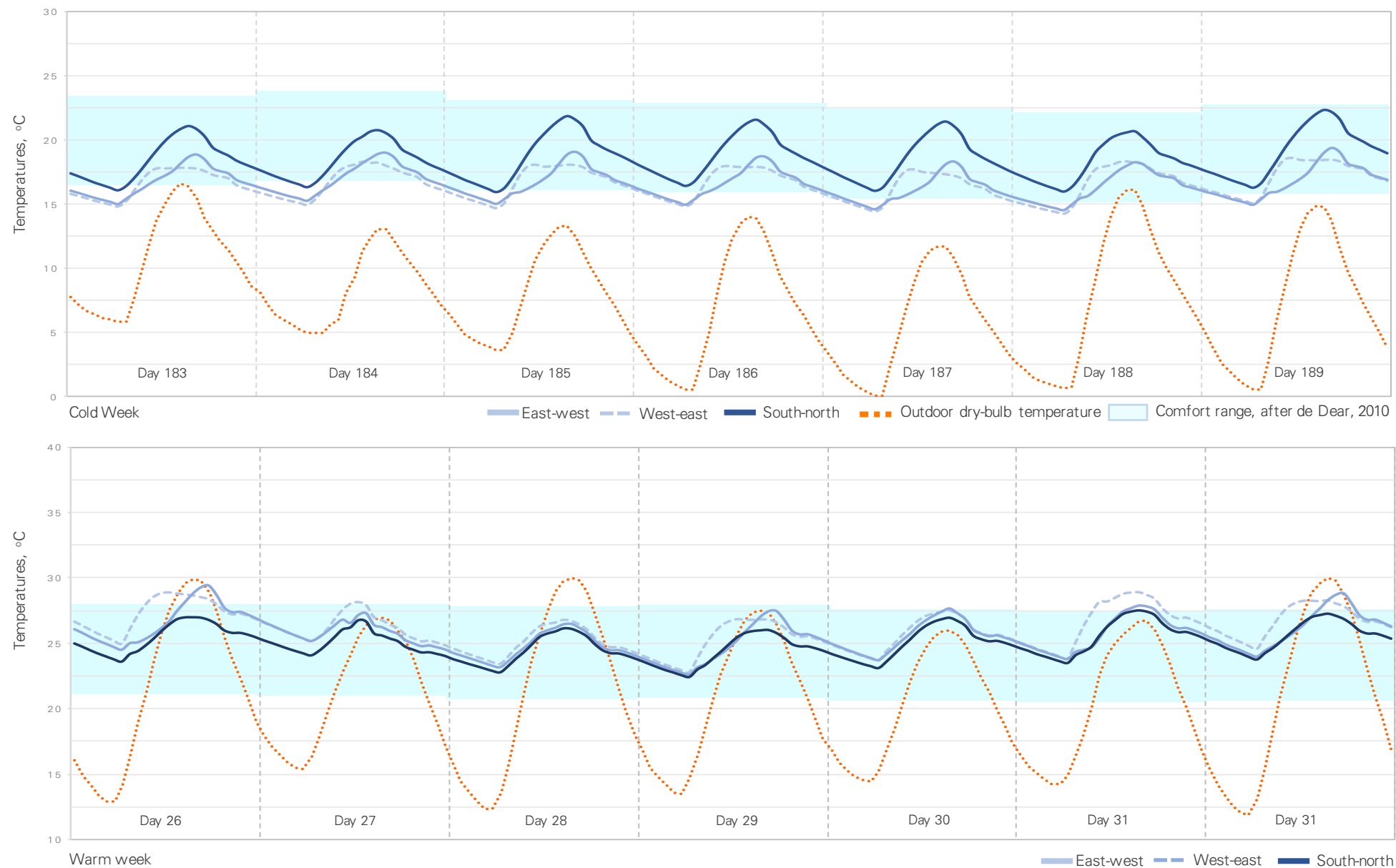


Figure 8.9.4 Effect of changing orientation of room window areas (single-storey detached)

The distribution of window areas in the base-case dwelling was improved to orient most of glazing areas toward the equator (based on results of simulations for the living area).

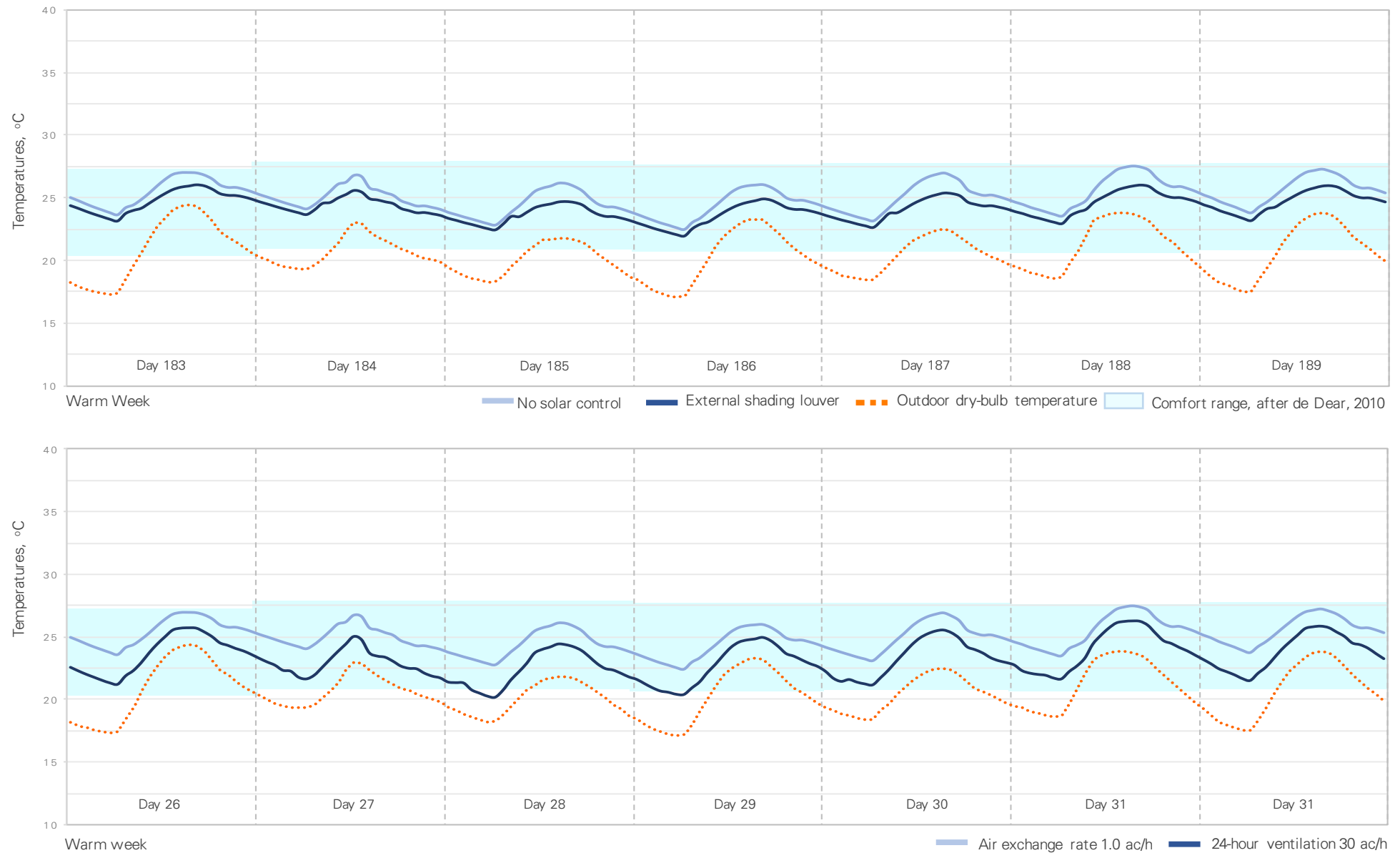


Figure 8.9.5 Effect of external shading blinds and opening windows (single-storey detached)

a) external window louvers are operated with their blinds positioned horizontally; b) half of room window area is assumed opened overnight, the equivalent of 10% room floor area (the resulting air exchange rate above is an average value obtained for the period over which windows were kept opened).

Figure 8.10 Parametric design improvements for the intermediate-floor apartment

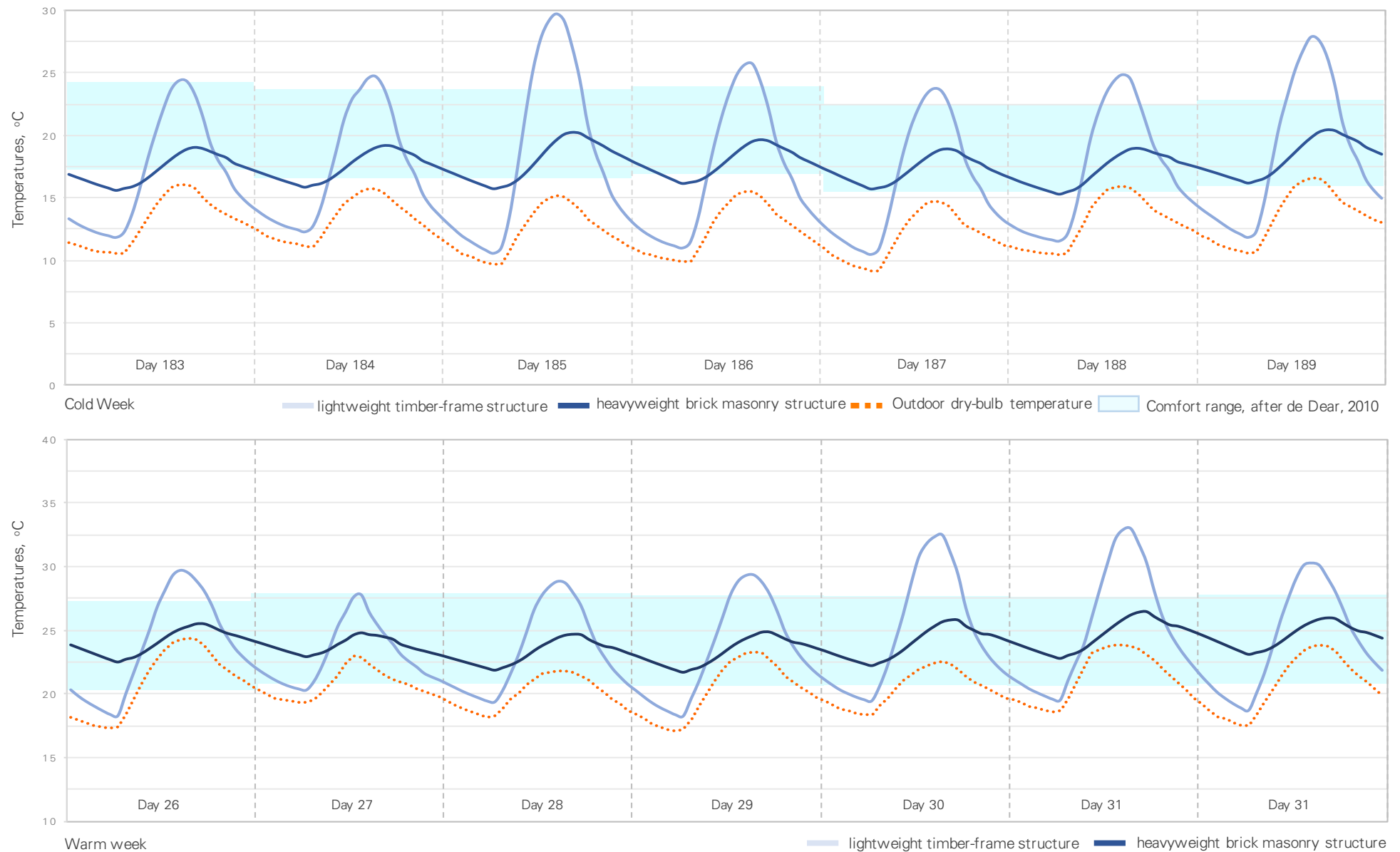
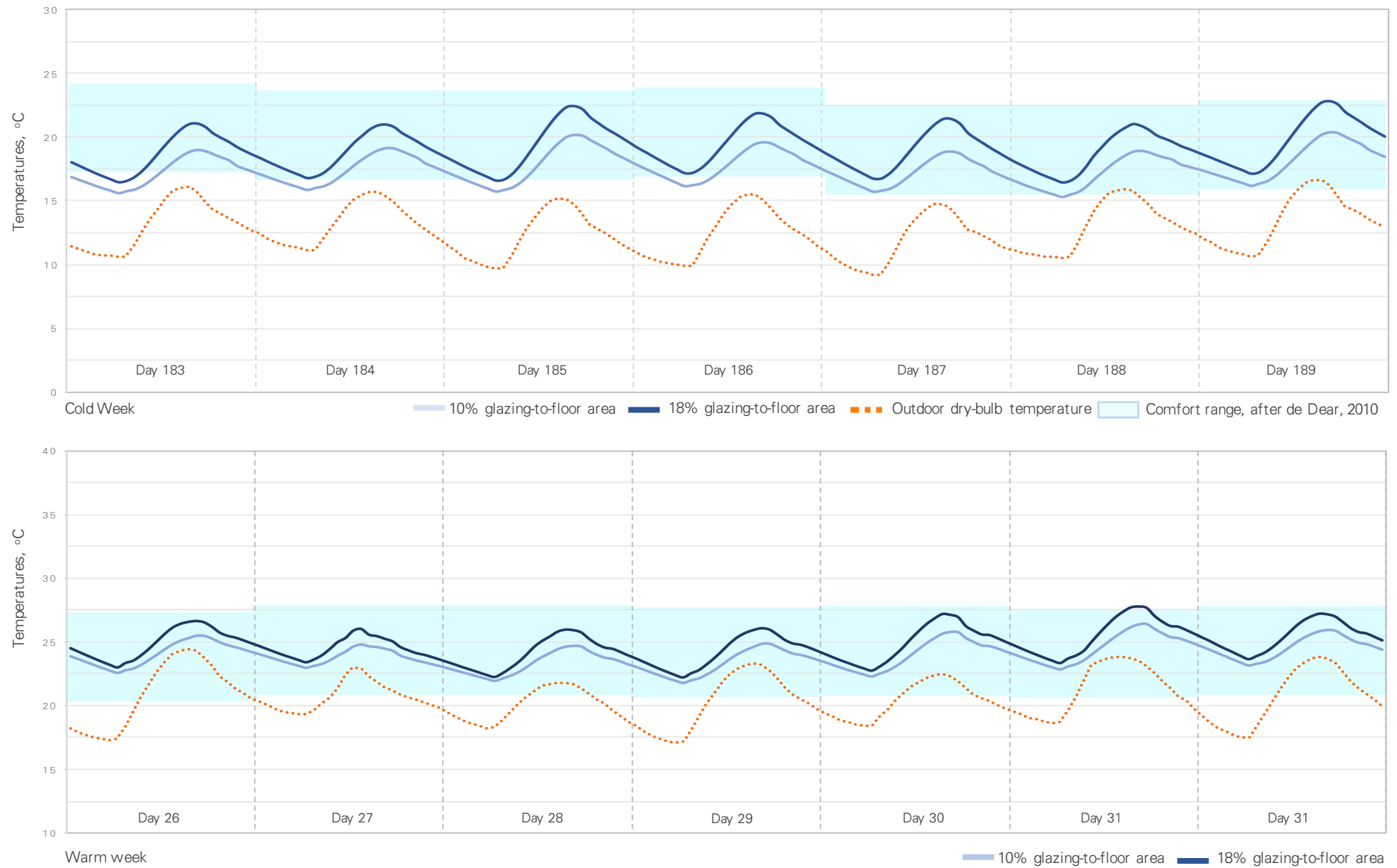


Figure 8.10.1 Effect of increasing building thermal capacity (intermediate-floor flat)

Typical timber-frame envelope structure is compared to a heavyweight masonry structure (traditional solid clay brick and light-concrete blocks with plaster finishes, see construction specifications in Figures 4.1 and 4.2). Both envelope structures consider minimum statutory insulation for exposed walls ($U = 4.0 \text{ W/m}^2\text{k}$)



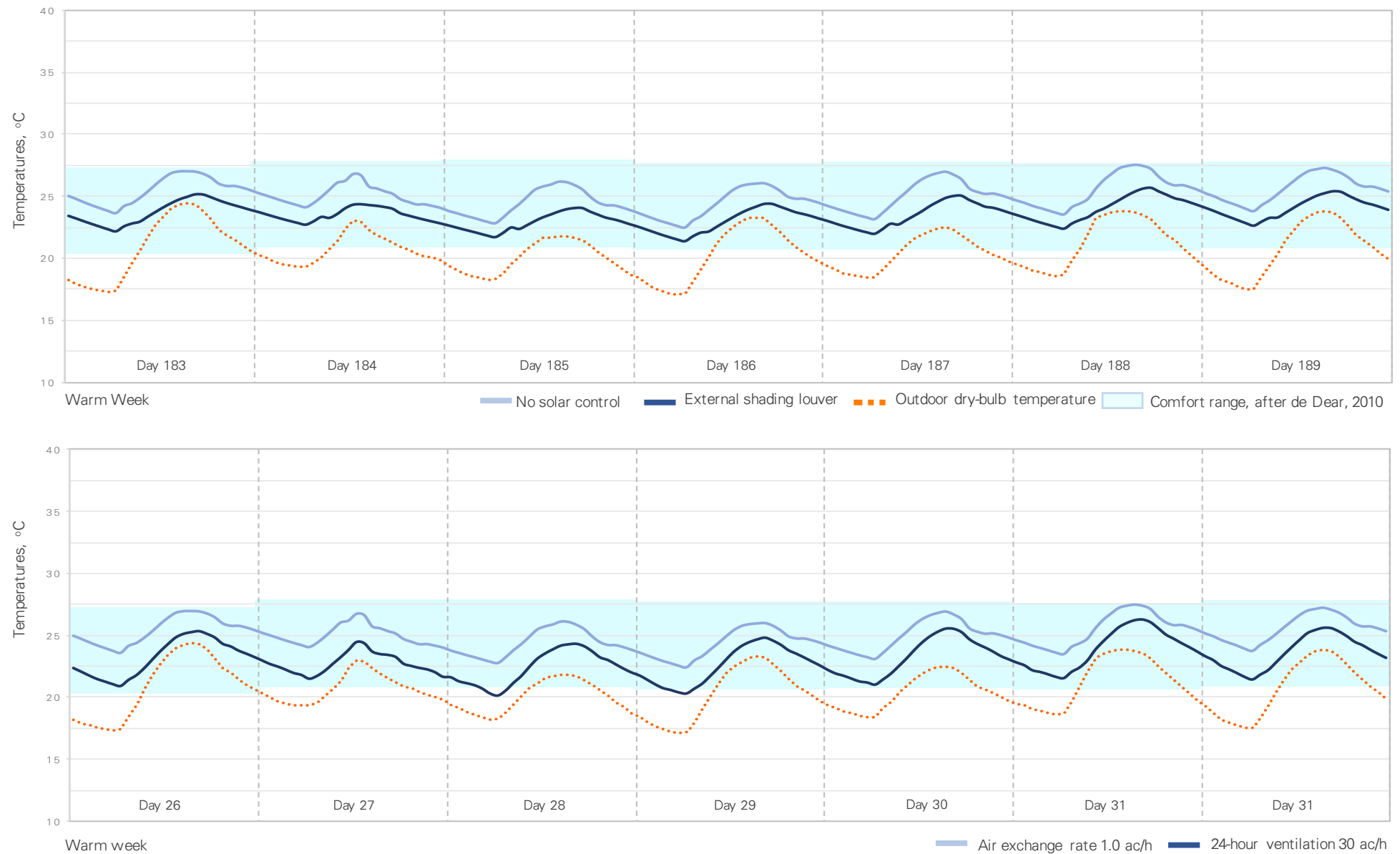


Figure 8.10.3 Effect of external shading blinds and opening windows (intermediate-floor apartment)

a) external window louvers are operated with their blinds positioned horizontally; b) half of room window area is assumed opened overnight, the equivalent of 9% room floor area (the resulting air exchange rate above is an average value obtained for the period over which windows were kept opened).

Figure 8.11 Results of building thermal simulations for Puerto Montt (41°S) Southern Coast (NCh-1079; INN, Of.2008)

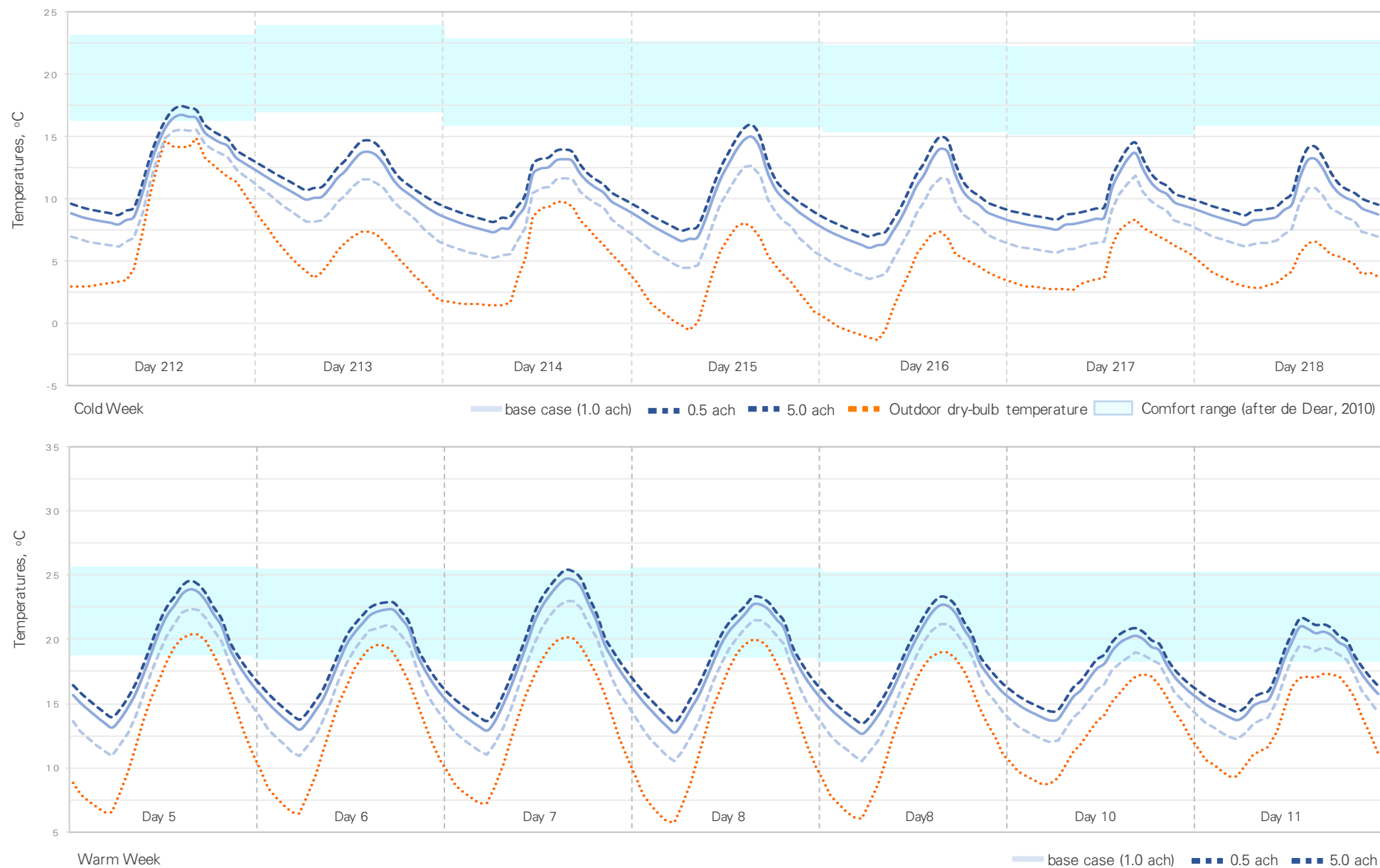


Figure 8.11.1 Effect of varying air-exchange rates (single-storey detached)

Different air-exchange rates are compared for the base-case of Santiago by changing infiltration rates in TAS. Three scenarios were investigated, based on blower door testing by Figueroa et al (2013): one for the lowest measured value of 0.5 ach, one for the average of 1.0 ach, and other for the highest value of 5.0 ach (see airtightness and ventilation criteria in section 3.4.3)

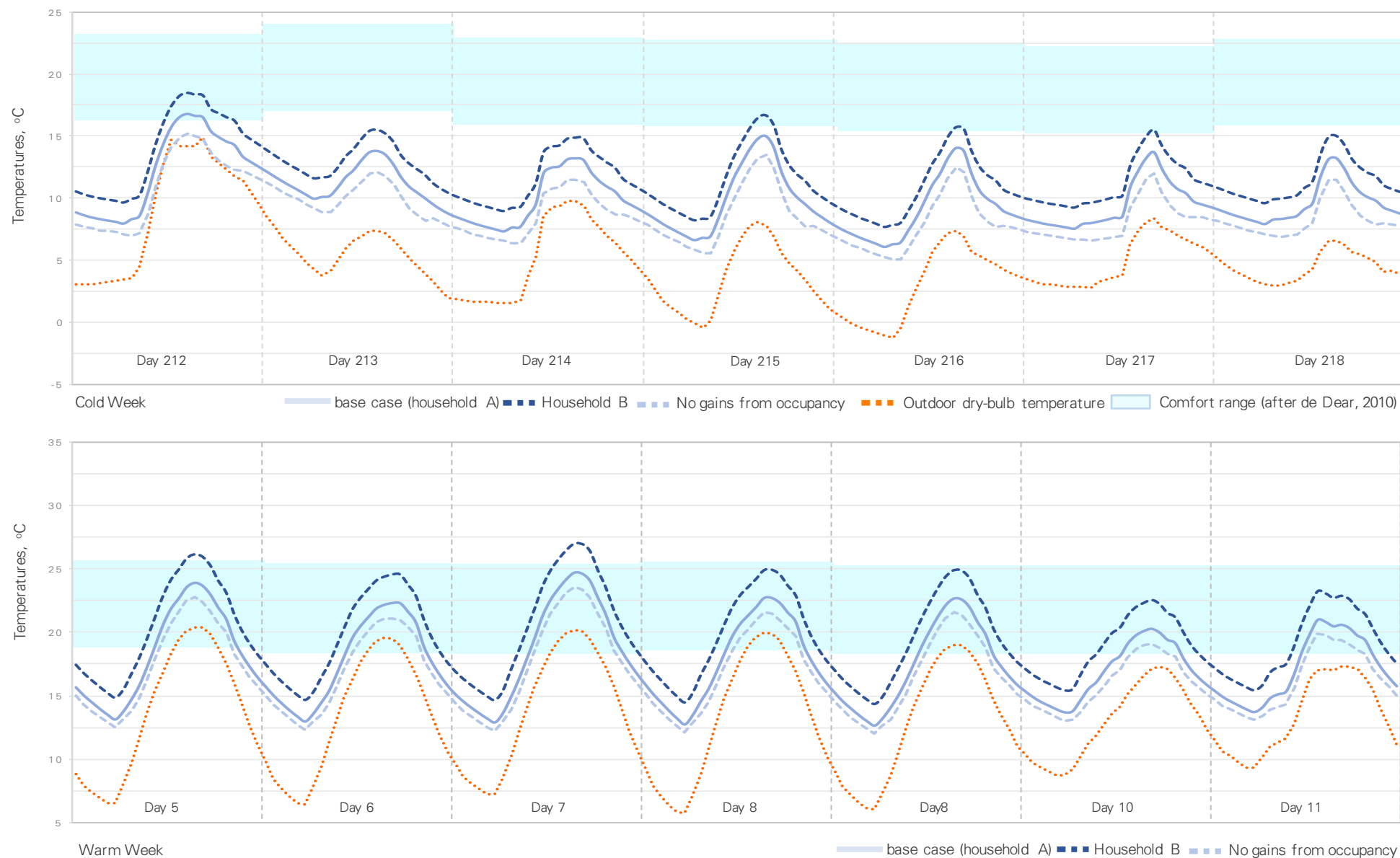


Figure 8.11.2 Effect of varying internal heat gains (single-storey detached)

Different internal heat gain loads are compared for the base-case of Santiago by changing hourly input assumptions in TAS. Three scenarios were investigated: one with no internal heat gains from occupants nor appliances; other for a household of four (*household A*), considering 5.0 W/m^2 per occupant, 5.0 W/m^2 for appliances in occupied rooms, and 10 W/m^2 for kitchen equipment (see hourly distribution in Table 3.5); and other for the same occupancy schedules (*Household B*) but increasing the number of occupants and heat gains from appliances by twofold

Figure 8.12 Parametric design improvements for the single-storey detached dwelling

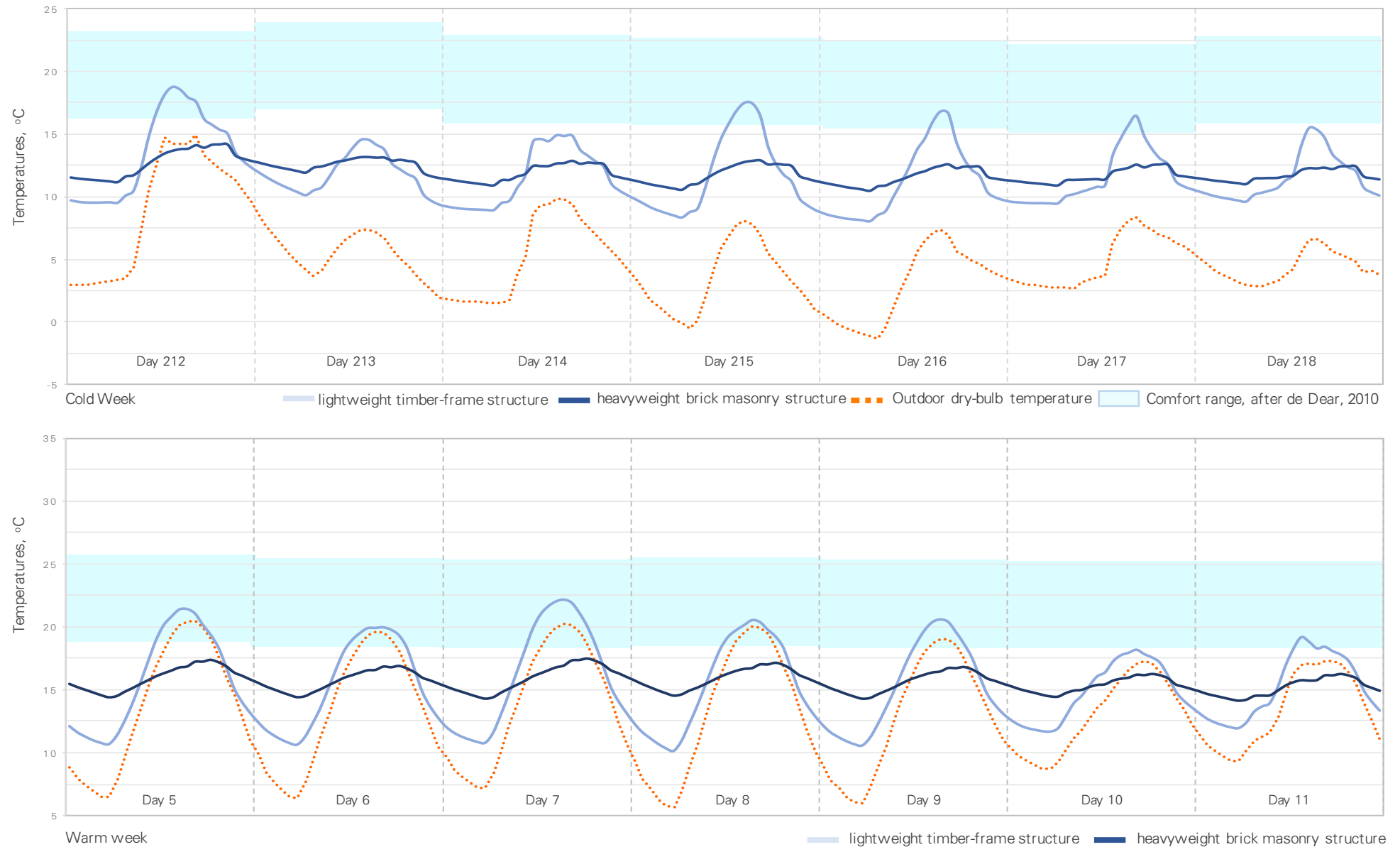


Figure 8.12.1 Effect of increasing building thermal capacity (single-storey detached)

Typical timber-frame envelope structure is compared to a heavyweight masonry structure (traditional solid clay brick and light-concrete blocks with plaster finishes, see construction specifications in Figures 4.1 and 4.2). Both envelope structures consider minimum statutory insulation for exposed walls ($U=1.1 \text{ W/m}^2\text{k}$) and roof elements ($U=0.3 \text{ W/m}^2\text{k}$).

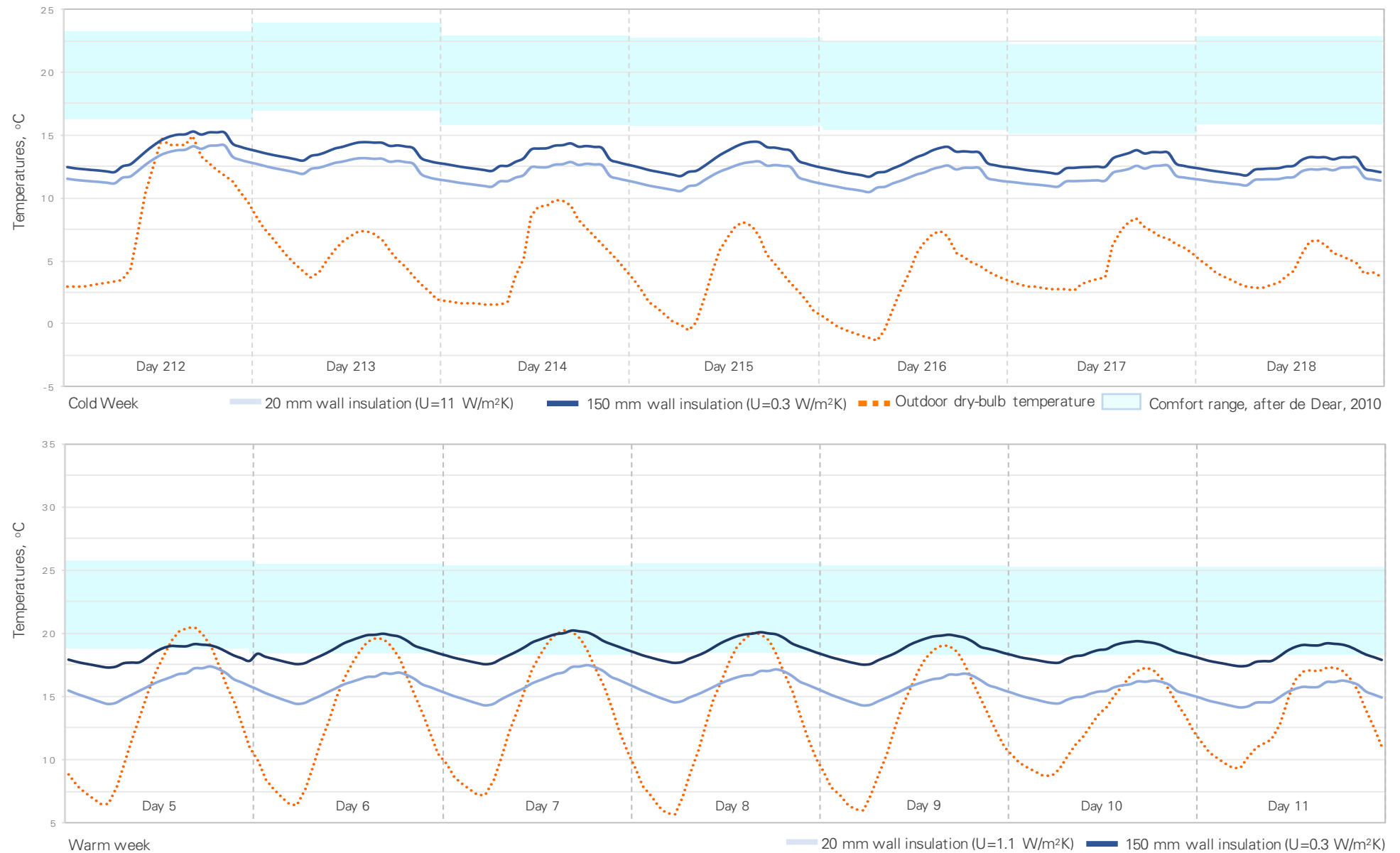


Figure 8.12.2 Effect of increasing walls thermal insulation (single-storey detached)

The thermal transmittance (U-value) of exposed wall elements is decreased from 1.1 W/m²K (CLT, 2007) to 0.3 W/m²K by increasing the thickness of external insulation (expanded polystyrene board) specified from 20 to 150 mm (based on results of simulations for the living area).

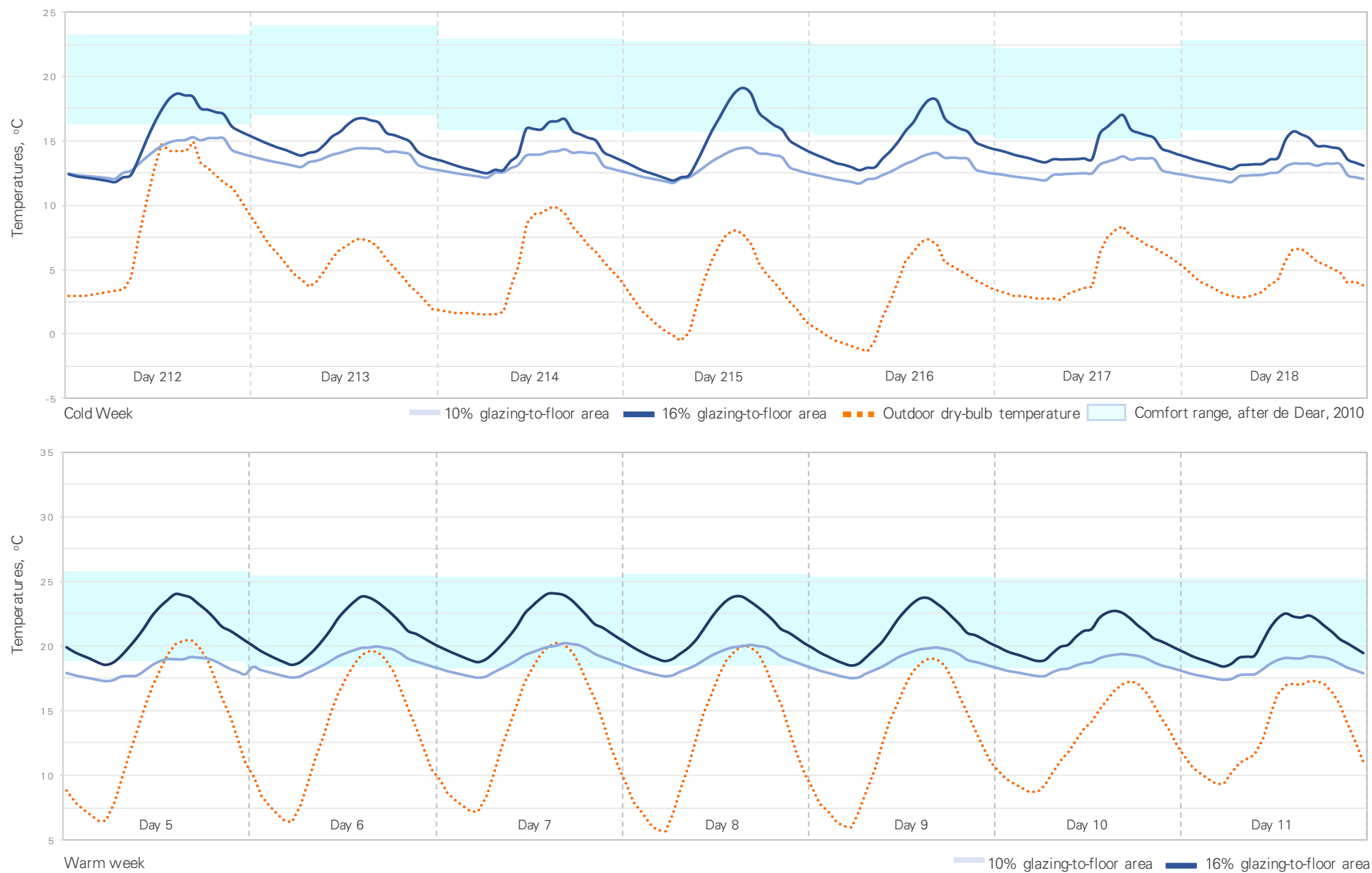


Figure 8.12.3 Effect of increasing the size of room glazing areas (single-storey detached)

For the windows of the base-case dwelling oriented towards the equator, room net glazing-to-floor areas are increased from 10% to 16% (based on results for the living area)

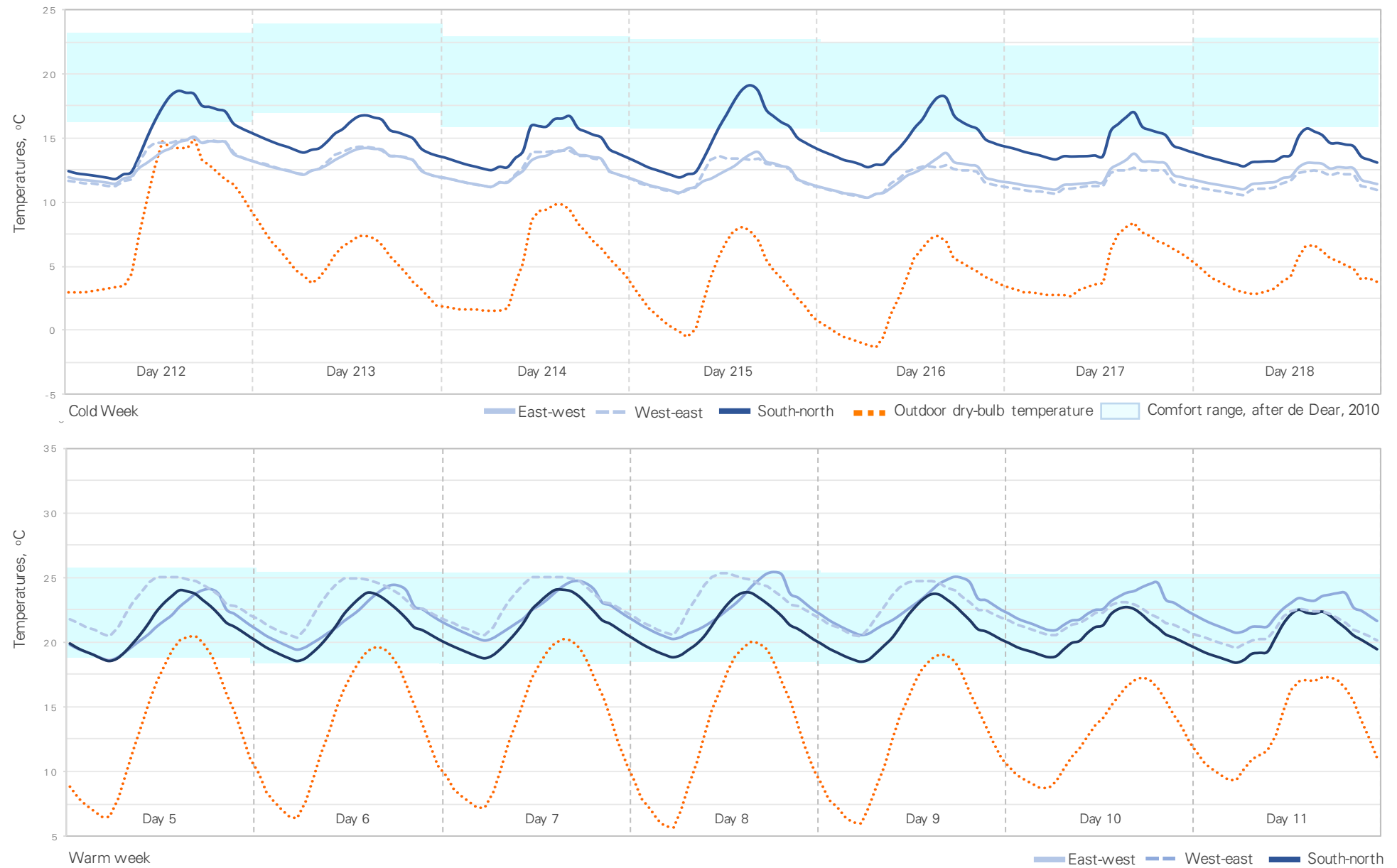


Figure 8.12.4 Effect of changing orientation of room window areas (single-storey detached)

The distribution of window areas in the base-case dwelling was improved to orient most of glazing areas toward the equator (based on results of simulations for the living area).

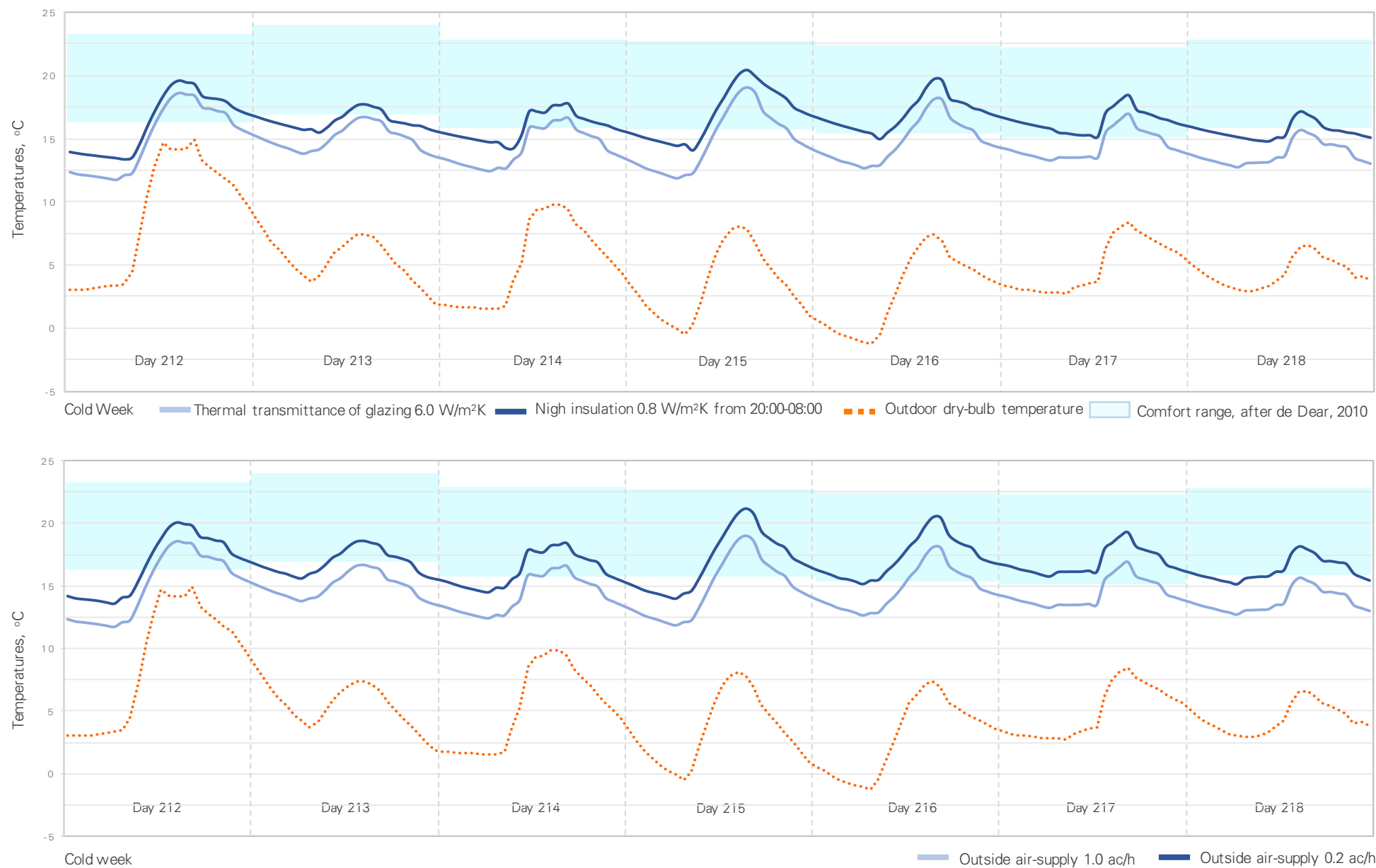


Figure 8.12.5 Effect of insulated shutters and window-frame vents (single-storey detached dwelling)

a) room thermal performance with and without use of internal blind shutters over night; b) outside air-supply rates are reduced by assuming window vents openings at minimum.

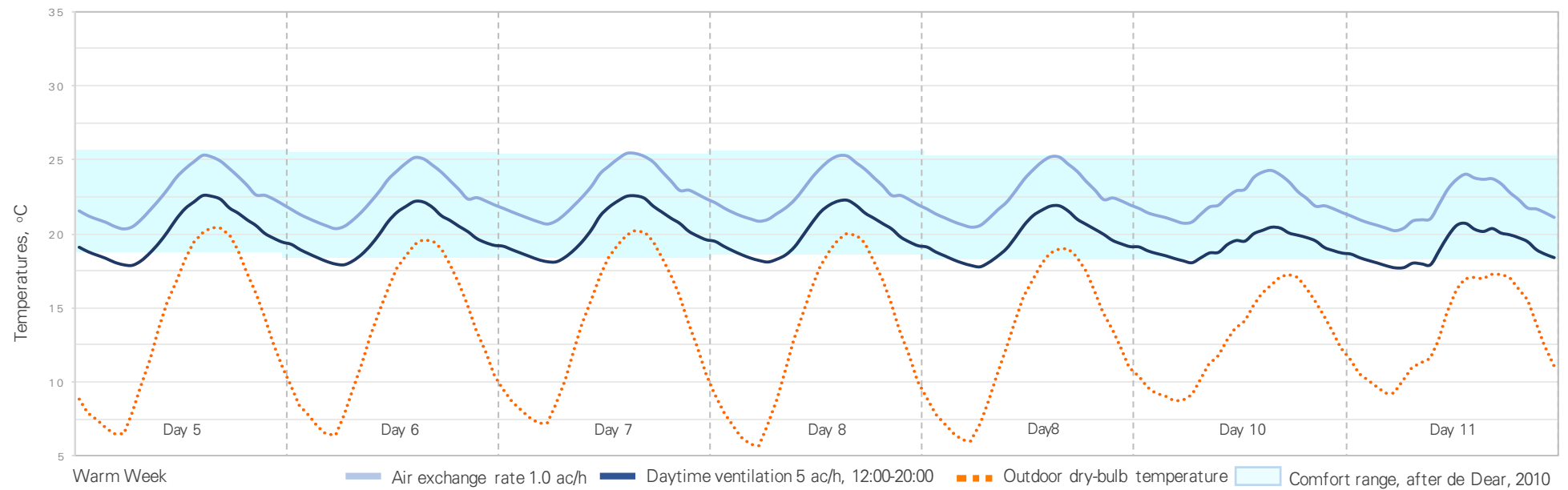


Figure 8.12.6 Effect of opening windows (single-storey detached dwelling)

half of room window area is assumed opened overnight, the equivalent of 8% room floor area (the resulting air exchange rate above is an average value obtained for the period over which windows were kept opened).

Figure 8.13 Parametric design improvements for the intermediate-floor flat

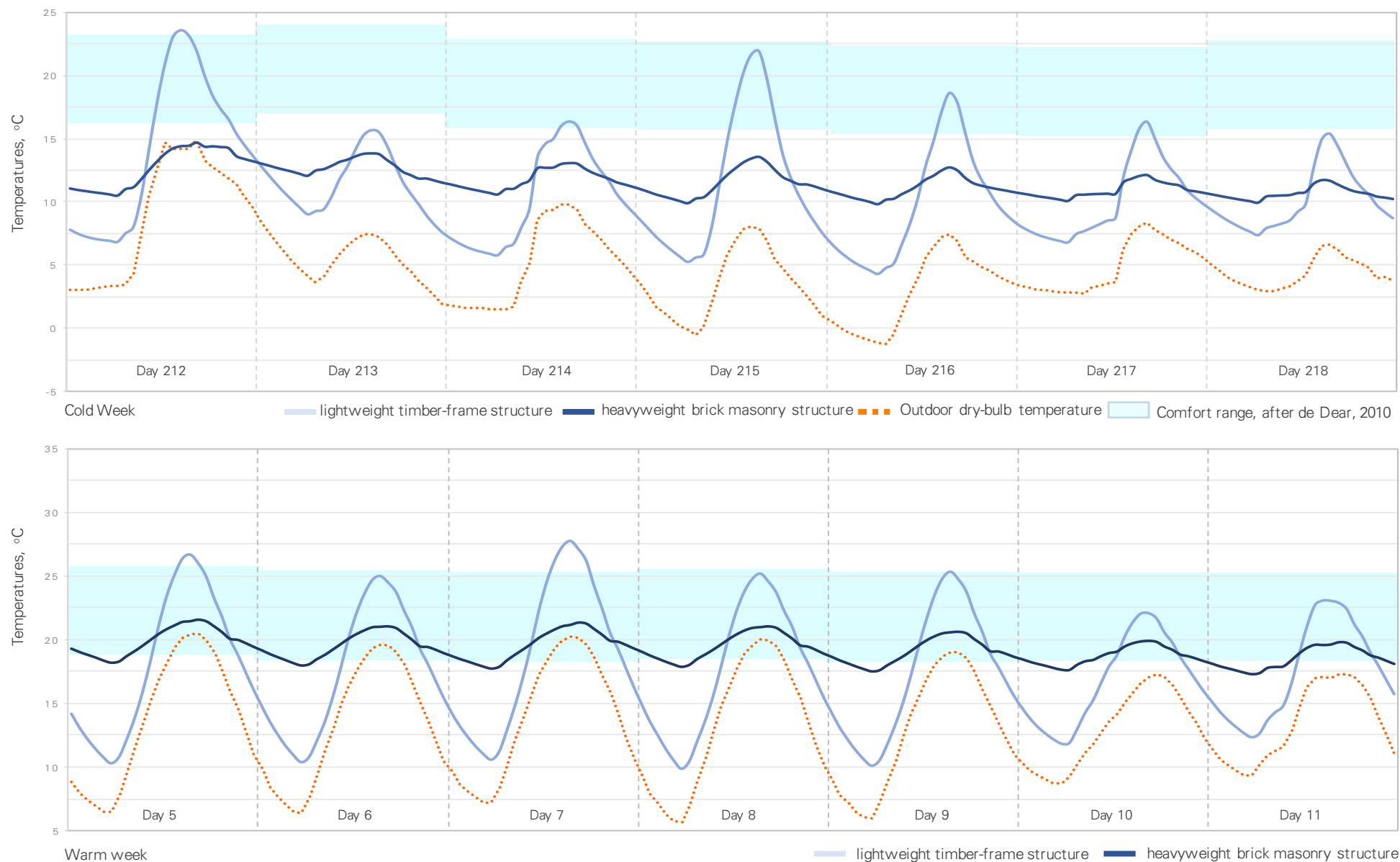


Figure 8.13.1 Effect of increasing building thermal capacity (intermediate-floor apartment)

Typical timber-frame envelope structure is compared to a heavyweight masonry structure (traditional solid clay brick and light-concrete blocks with plaster finishes, see construction specifications in Figures 4.1 and 4.2). Both envelope structures consider minimum statutory insulation for exposed walls ($U=1.1 \text{ W/m}^2\text{k}$)

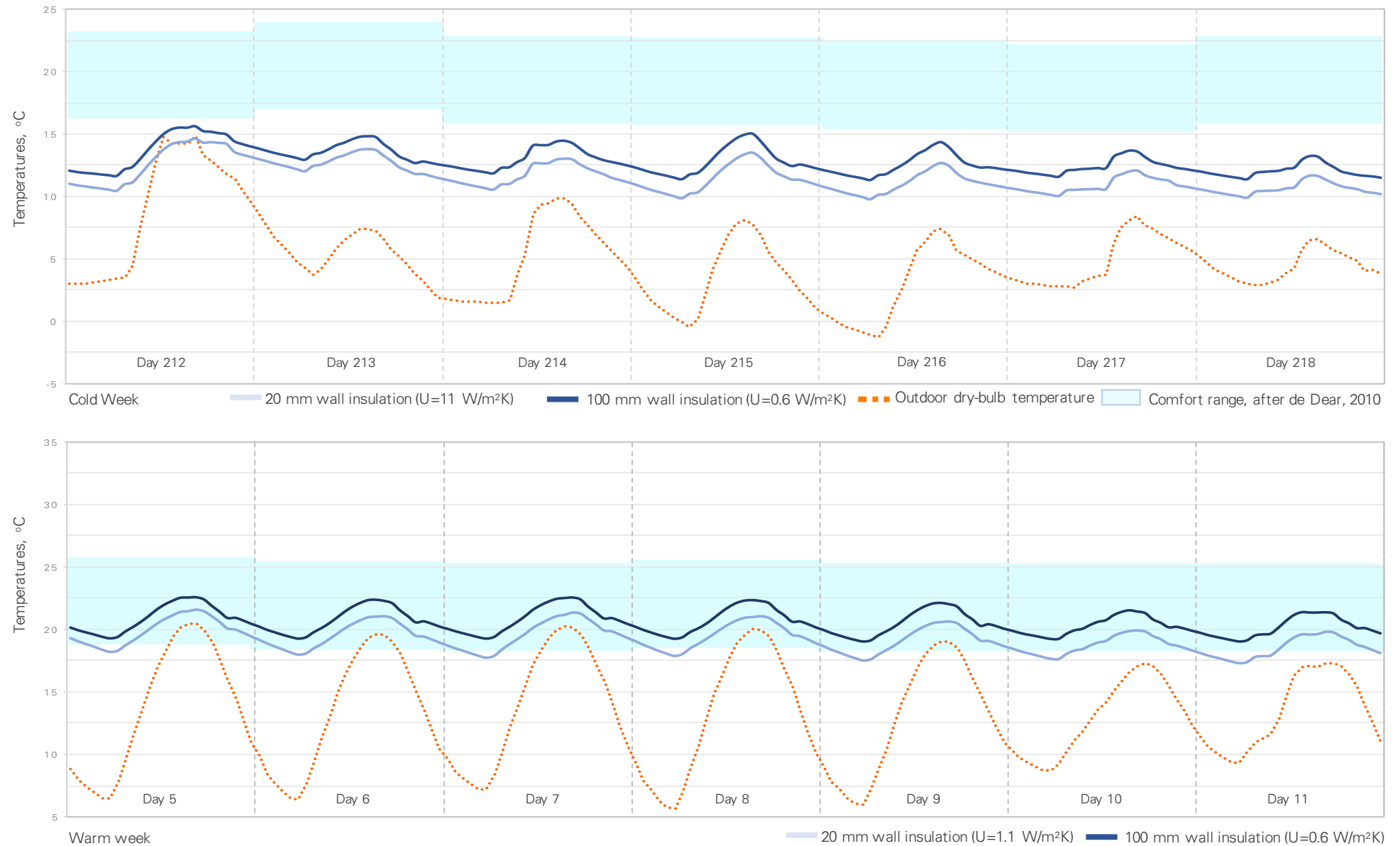


Figure 8.13.2 Effect of increasing wall thermal insulation (intermediate-floor apartment flat)

The thermal transmittance (U-value) of exposed wall elements is decreased from 1.1 W/m²K (CLT, 2007) to 0.6 W/m²K by increasing the thickness of external insulation (expanded polystyrene board) specified from 20 to 100 mm (based on results of simulations for the living area).

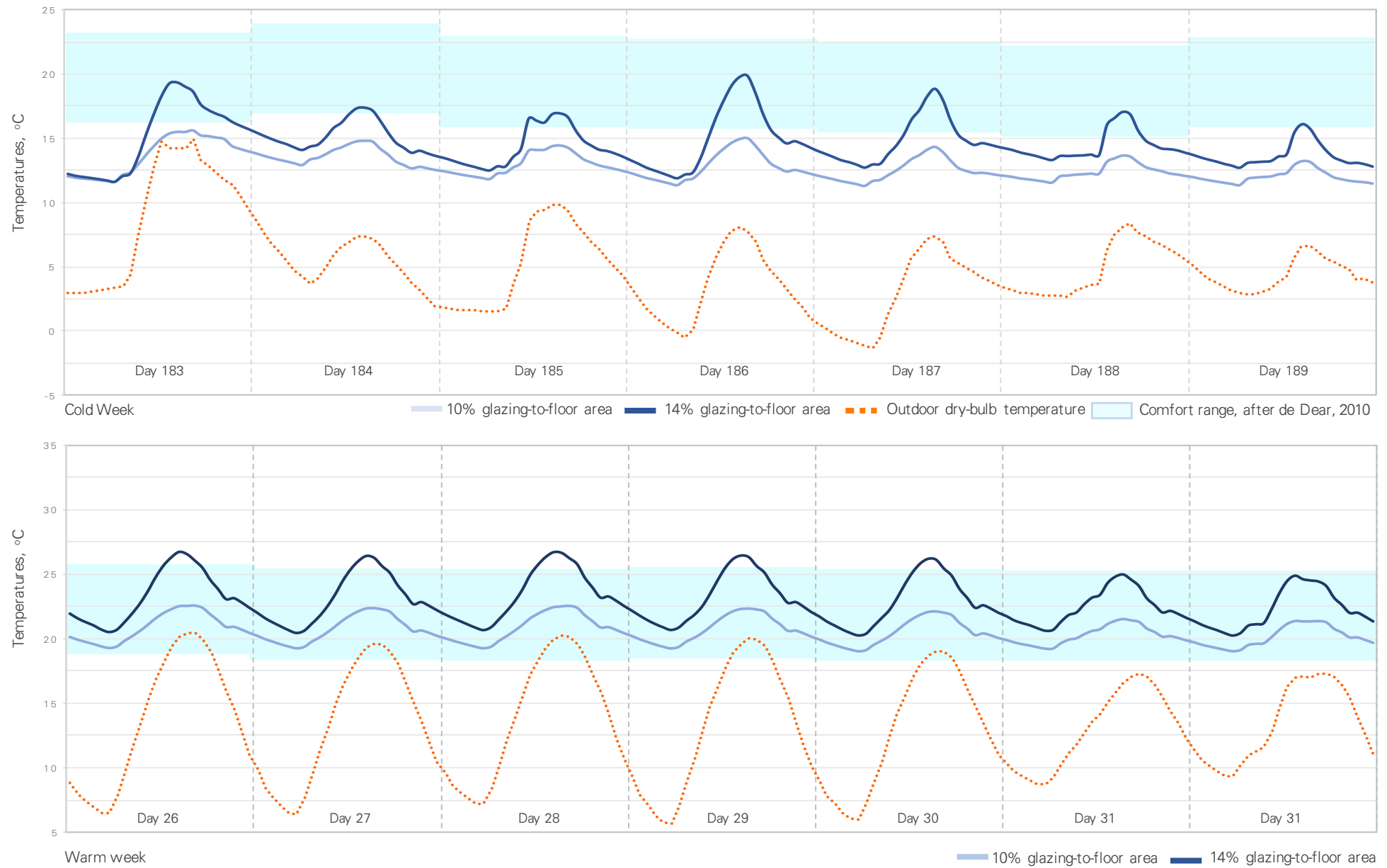


Figure 8.13.3 Effect of increasing the size of room glazing areas (intermediate-floor apartment)

For the windows of the base-case dwelling oriented towards the equator, room net glazing-to-floor areas are increased from 10% to 14% (based on results for the living area)

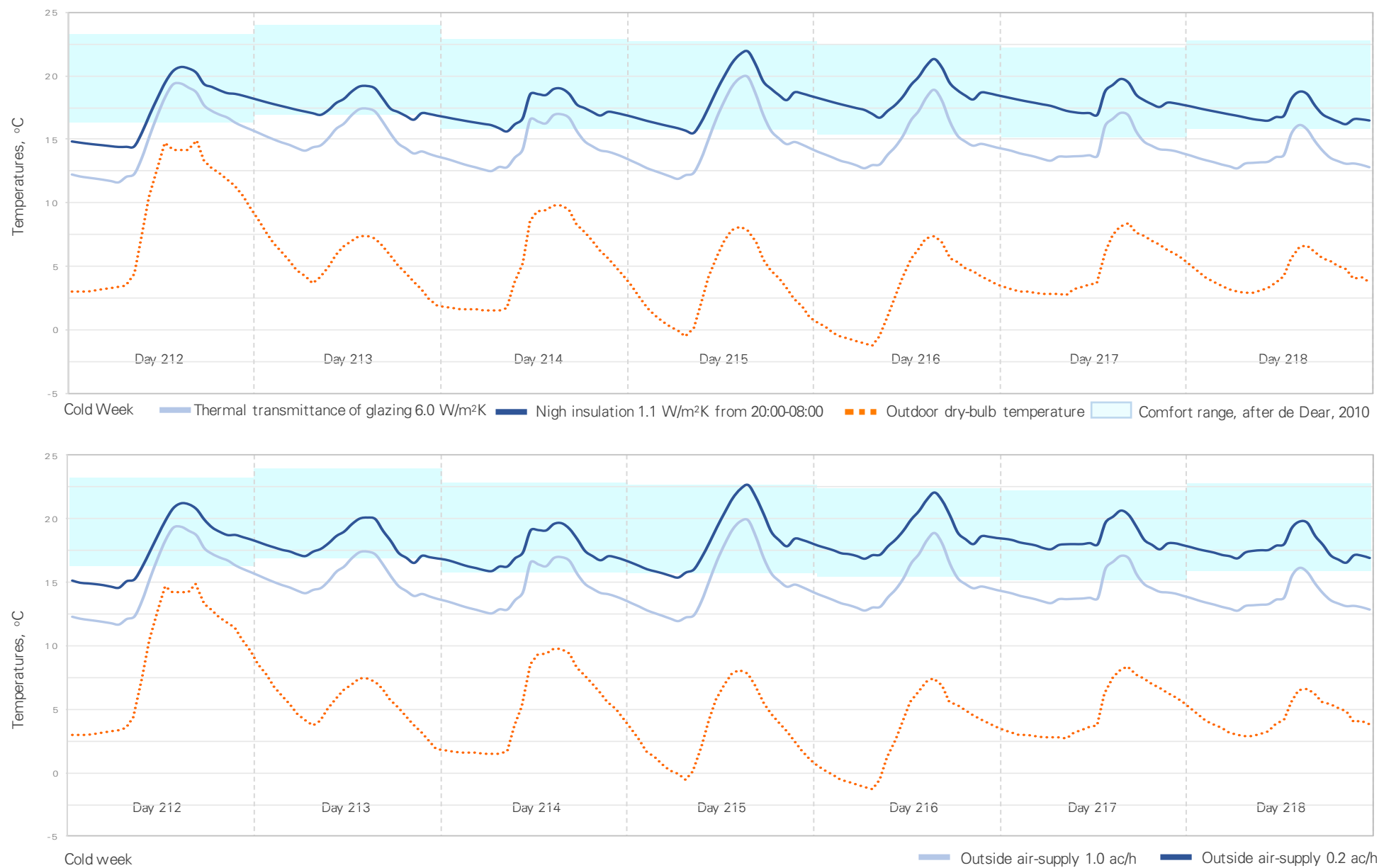


Figure 8.13.4 Effect of insulated shutters and window-frame vents (intermediate floor apartment)

a) room thermal performance with and without use of internal blind shutters over night; b) outside air-supply rates are reduced by assuming window vents openings at minimum.

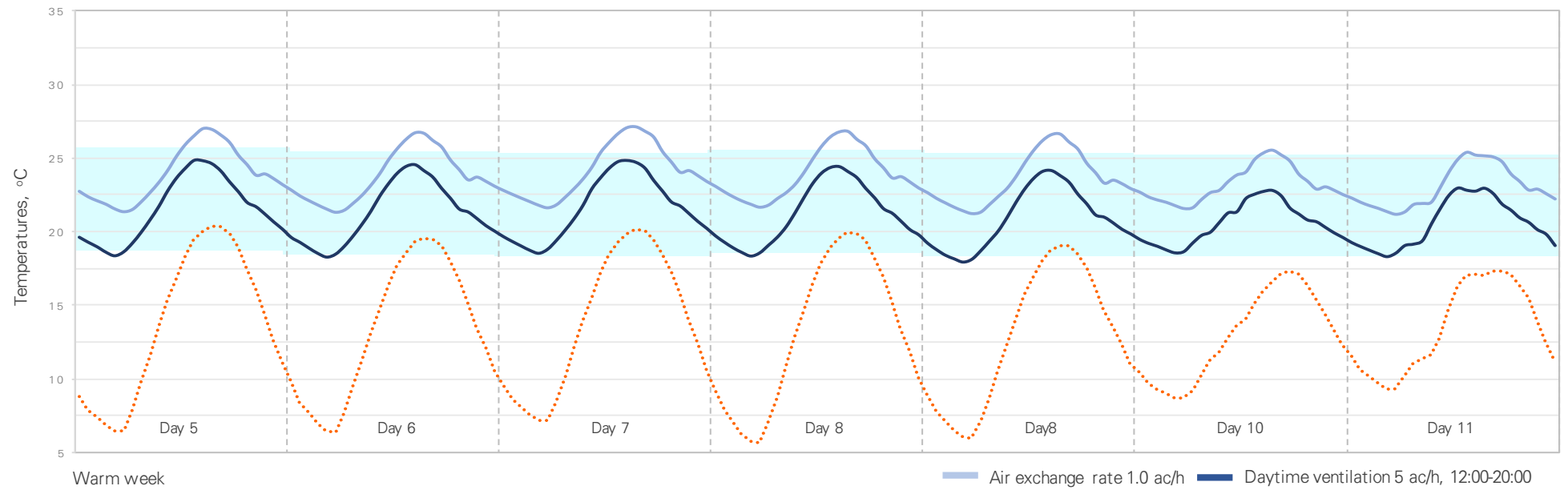


Figure 8.13.5 Effect of opening windows (intermediate-floor apartment)

b) half of room window area is assumed opened overnight, the equivalent of 7% room floor area (the resulting air exchange rate above is an average value obtained for the period over which windows were kept opened).